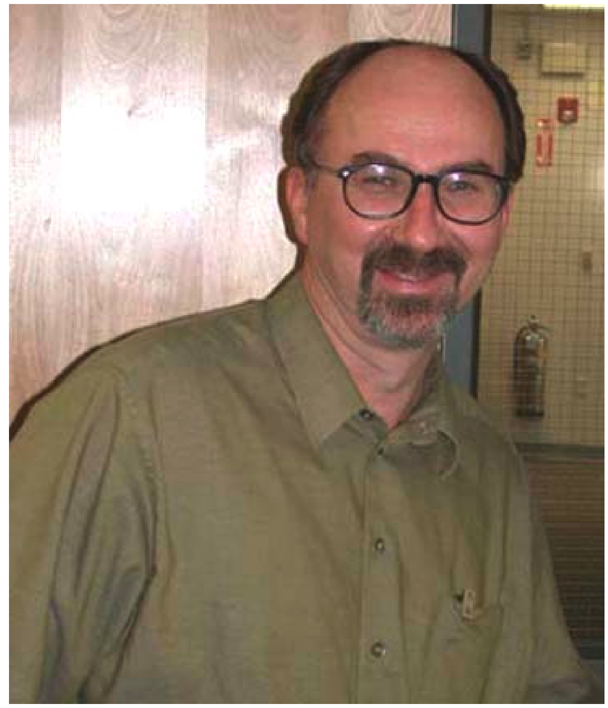
CHAPTER 3 CLOCKS FOR NAVIGATION and INERTIAL NAVIGATION AND RESOURCE LOCATION TECHNOLOGIES




TALSO
CHUI

Clocks for Navigation

by Bob Silberg, Raytheon

A session on development of clocks for navigation began with JPL's Stephen Lichten, who discussed the role of atomic clocks in potential GPS systems at the Moon and Mars. He said the goal of future study should be to determine how GPS-like tracking capability can be enabled with fewer than four GPS satellites in view.

Kurt Gibble of Pennsylvania State University pointed out that the ground-based DSN currently experiences different atmospheric delays in spacecraft signals and that space-based clocks offer an advantage in this regard. He added that, to track assets on Mars from Earth orbit, we would need very good clocks, while less performance would be required of clocks in GPS systems orbiting Mars.

John Prestage of JPL spoke about a small ultra-stable mercury-ion-trap clock for onboard spacecraft navigation. It is microgravity- and 1G-friendly, and has the advantage of simplicity since it requires no lasers, cryogenics, or microwave cavities.

JPL's Bill Klipstein provided an overview of the importance of clocks in planetary navigation, saying that they are the backbone of high-performance GPS and are needed for precise landing, orbital rendezvous, and aerobraking. He made the case that OBPR has invested heavily in assembling a unique team with the appropriate technical background and understanding needed to devise a GPS concept for Mars. Such a system would support one-meter autonomous surface positioning for one month, with no updates and a sparse navigation constellation for long-range crew and rover deployments. He said a global system is needed because we're talking about sending people over spans of hundreds of kilometers.

Konstantin Penanen, also of JPL, discussed a clock using superfluid helium, which he said would be more predictable than a solid-state system, and better than many mechanical systems.

Inertial Navigation and Resource Location Technologies

Mark Kasevich of Stanford University presented a talk about atom interferometer sensors based on atom de Broglie wave interference. He said that the quantum mechanical wave-like properties of atoms can be used to sense inertial forces. Such a device can be used in accelerometers, gyroscopes, and gravity gradiometers. Atom interferometers offer 10 to 100 times improvement in detection sensitivity at reduced instrument costs.

Nan Yu of JPL similarly discussed atom interference inertial sensors for space applications. He said that cold-atom inertial sensor technology can contribute significantly to resource exploration, and to location and navigation in space. He said JPL is developing toward a cold-atom gravity gradiometer for space.

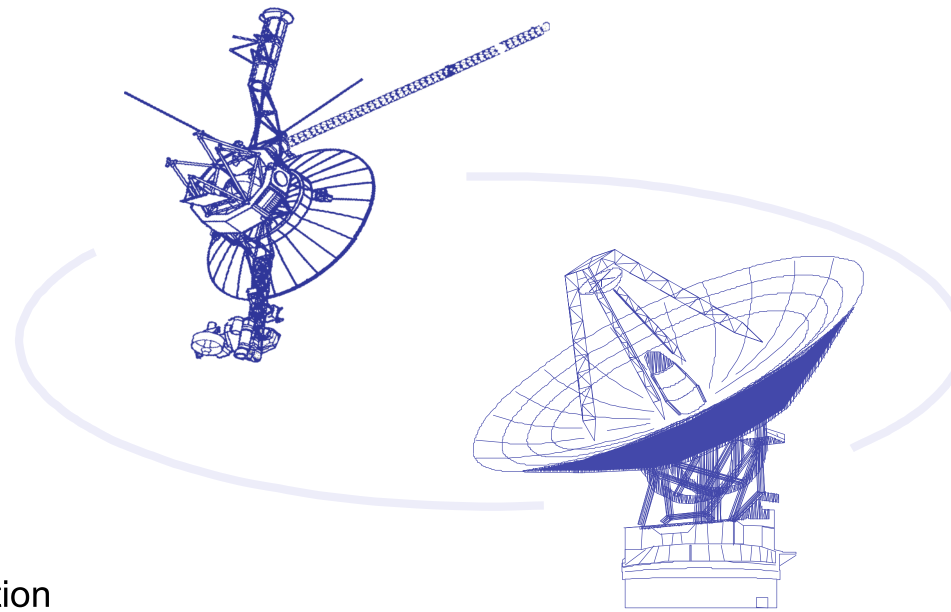
Ho Jung Paik of the University of Maryland spoke about exploring the Moon with an orbiting superconducting gravity gradiometer (SGG). He pointed out that high radiation levels on the lunar surface make underground cavities desirable as living quarters for astronauts. One way to detect such cavities and other underground resources, he said, is by surveying with a sensitive superconducting gravity gradiometer flying in a low-altitude orbit. Paik also emphasized that his SGG has demonstrated, already10 years ago, sensitivities 10^4 times better than anything shown to date by atom interferometers, and that a SGG in the microgravity of space will have sensitivity improved another 10^4 times.

JPL's Talso Chui declared that applied superconductivity and superfluidity can help meet a number of challenges related to planetary exploration. He discussed the merits of superfluid gyroscopes and clocks, and superconducting clocks. He said that SQUID-based transient electromagnetics can help to find water, caves, and minerals, and can be used in mini-MRIs to monitor astronauts' brain functions.

Emile Hoskinson a graduate student in Richard Packard's group at the University of California, Berkeley, suggested that superfluid gyroscopes for geodesy and seismology are feasible. He said that a ^{4}He dc-interference gyroscope may well be demonstrated in the near future, and that of the high-precision Sagnac interferometers, such a ^{4}He device could be one of the most inexpensive, practical, and portable. He pointed out that liquid ^{4}He is three orders of magnitude (in temperature) easier to work with than liquid ^{3}He.

Applications of Clocks to Space Navigation & “Planetary GPS”

April 20, 2004



Stephen M. Lichten
Jet Propulsion Laboratory
Manager, Tracking Systems and Applications Section

*This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

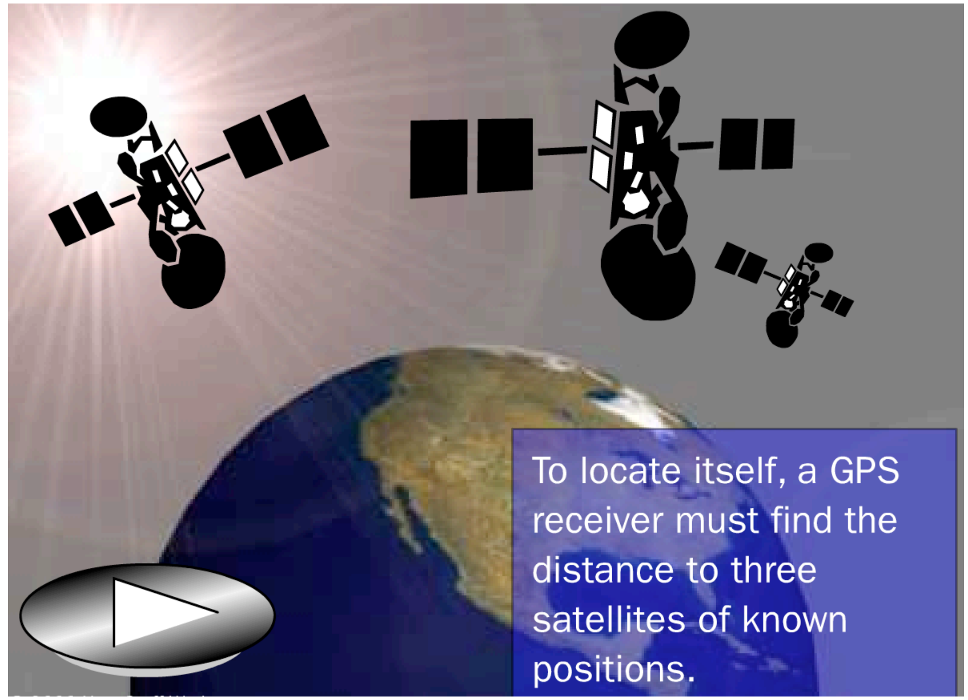
Outline of Presentation

- How GPS "works" for tracking and navigation at Earth
- Importance of clocks for GPS
- Deep Space Tracking
- Concepts for communications/navigation systems at other planetary bodies
- Sparse GPS-like planetary systems and tracking/navigation

Applications of Clocks to Space Navigation & “Planetary GPS”

How GPS Works

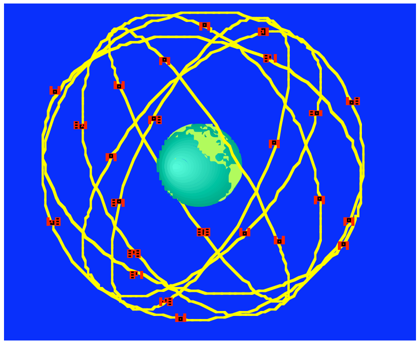
- GPS determines user position via “triangulation” to three GPS satellites
- The user’s GPS receiver compares each satellite’s unique pseudorandom code to models stored in the receiver to measure the time delay, and hence distance, to each GPS satellite
  - Requires that all GPS satellites be “synchronized” to “same” time
  - User does not need a good clock: a fourth GPS measurement determines the user time offset from “GPS time”
- Each GPS satellite continuously broadcasts its ephemeris and offset from “GPS time,” which is defined precisely relative to highly stable ground clocks. With these data, a GPS user receiver can in real-time uniquely determine its location (and time offset from “GPS time”) by tracking four GPS satellites

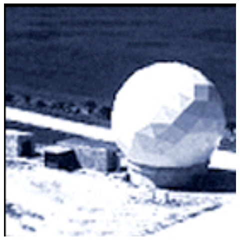


Each GPS satellite transmits a unique pseudorandom code

How GPS Works (cont.)

- **Operational Control Segment (OCS).** The USAF OCS consists of one Master Control Station (MCS) at Schriever AFB in Colorado Springs, plus monitor stations at the MCS, Hawaii, Kwajalein, Diego Garcia and Ascension Island. The stations passively track ranging data from all GPS in view. The MCS estimates and predicts each **satellite's ephemeris** and **clock** parameters and periodically uploads them to each GPS for re-transmission in its navigation message.

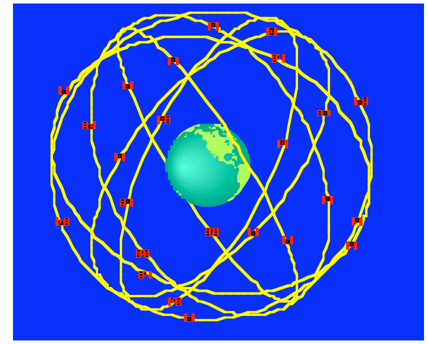


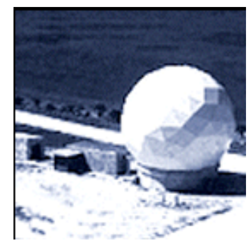


GPS MCS

- GPS ephemeris/clock uploads are updated every several hours. During that time period, the broadcast ephemeris degrades only moderately because …
  - GPS are in relatively high-altitude, well-behaved orbits
  - GPS all carry precise (atomic) clocks
  - Knowledge of GPS time is maintained through the very stable ground clocks at the ground tracking sites

- **The Design Trade for GPS.** The GPS designers incorporated …
  - Accurate (atomic) clocks at operational ground tracking sites and onboard the GPS satellites
  - A 24/7 global tracking network to accurately and continuously determine and update GPS orbits and clocks
  - *In contrast: the GPS user typically carries relatively simple equipment and does not require a good clock*
- The U.S. government elected to invest in robust and reliable GPS space and ground/control segments (infrastructure), thus enabling the user segment (millions of users) to carry relatively simple and cheap user equipment
- Roughly $12B to develop GPS (in 1980s)





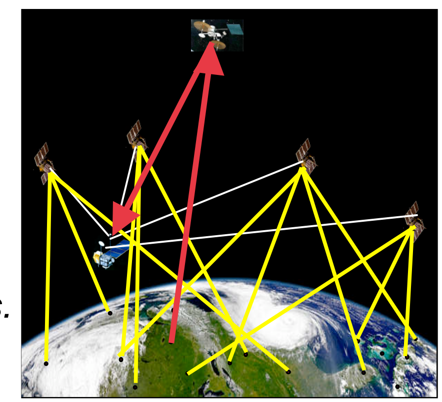
GPS MCS

Applications of Clocks to Space Navigation & "Planetary GPS"

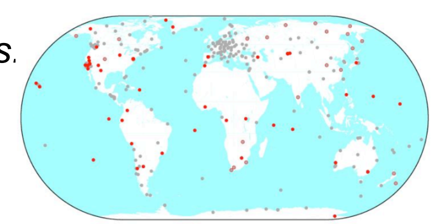
GPS Performance Today

- Standalone commercial receiver (handheld, autos, boats etc.)
  - **10 meters** real-time positioning.
    - *Performance is limited by GPS clock & orbit modeling.*

- Commercial receiver with differential services
  - **2 meters** real-time positioning. Requires local/regional differential service subscription.
    - *Performance is limited by GPS clock & orbit modeling.*



- JPL precision global differential GPS (GDGPS) system
  - **10 cm** real-time positioning accuracy. Requires global differential service from commercial partner.
    - *Network processing improves orbits and eliminates dependence on clocks.*
- Non-real-time (minutes to days) geodetic positioning
  - Better than **1-cm** non-real-time positioning accuracy. Requires global network data + special software.
    - *Network processing improves orbits and eliminates dependence on clocks.*

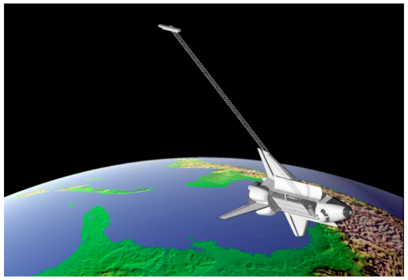


Applications of Clocks to Space Navigation & "Planetary GPS"

Spacecraft Navigation with JPL Blackjack GPS Receivers

Jet Propulsion Laboratory
California Institute of Technology

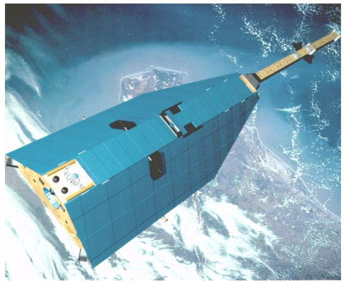
Of all these, only the GRACE GPS receivers carried high-quality clocks (USOs).



45-cm accuracy

SRTM

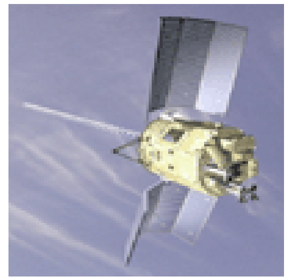
Feb 2000



4-cm accuracy

CHAMP

Jul 2000



4-cm accuracy

Sub-meter real-time demo

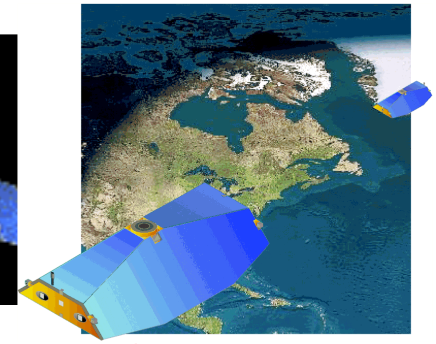
SAC-C

Nov 2000

1-cm accuracy

JASON-1

Dec 2001



1-cm accuracy

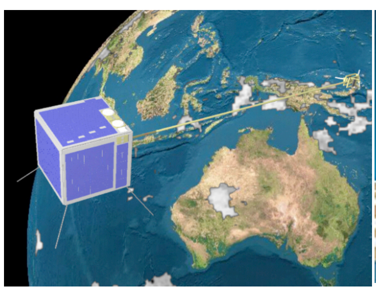
GRACE

Mar 2002

Missions In Development

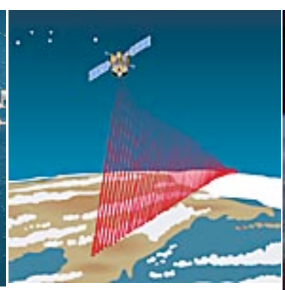
Dec 2002

FedSat



Dec 2002

ICESat



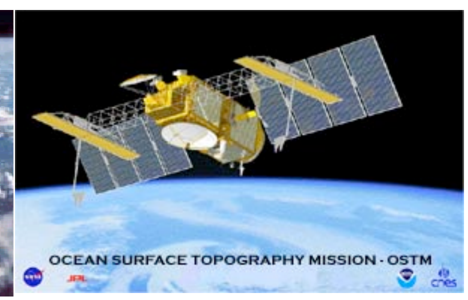
5-cm accuracy

Sept 2005

COSMIC

2008

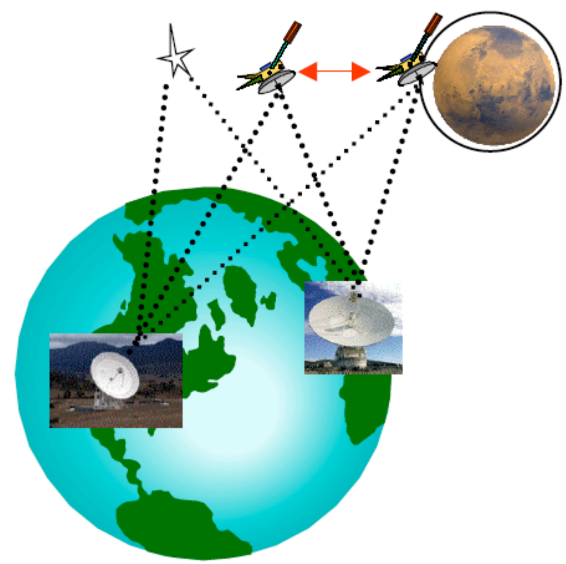
OSTM



>12 years of on-orbit performance

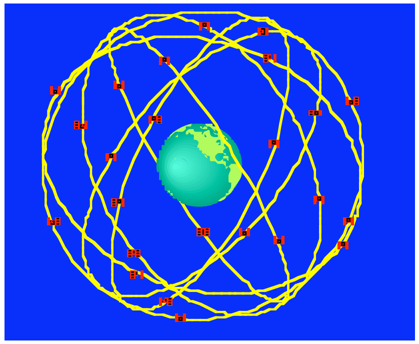
Deep Space Tracking

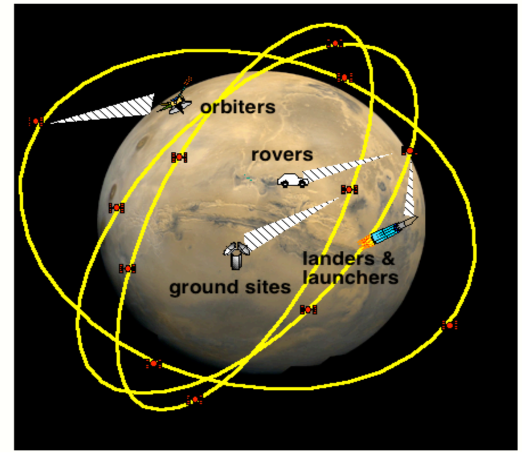
- Challenges of deep space tracking from Earth
  - Weak signals
    - NASA Deep Space Network uses 70-m and 34-m antennas
  - Geometry and visibility
  - Light travel time from Earth
    - 5 to 25 minutes to Mars
    - ~ 1.3 sec to Moon
  - Reference frame issues
- Typical data types
  - Two-way Doppler, 0.03 mm/s
  - Two-way range, 2 meters
  - Delta-Differential one-way range, VLBI
    - 2 nrad = 0.06 nsec = 1.2 cm delay
  - Optical navigation

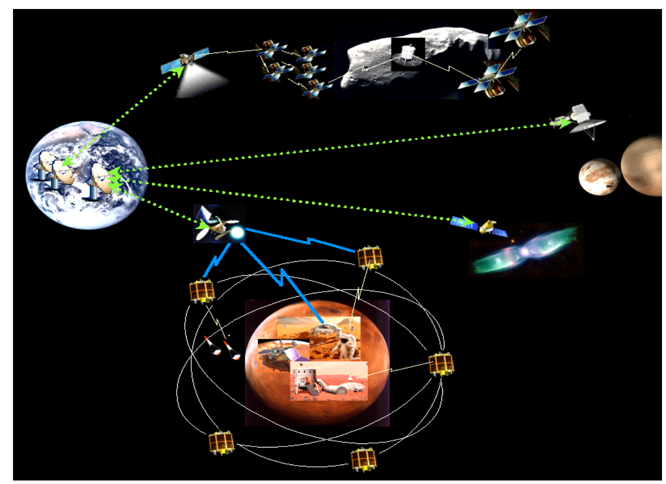


Applications of Clocks to Space Navigation & "Planetary GPS"

"In Situ" Tracking at Other Planetary Bodies



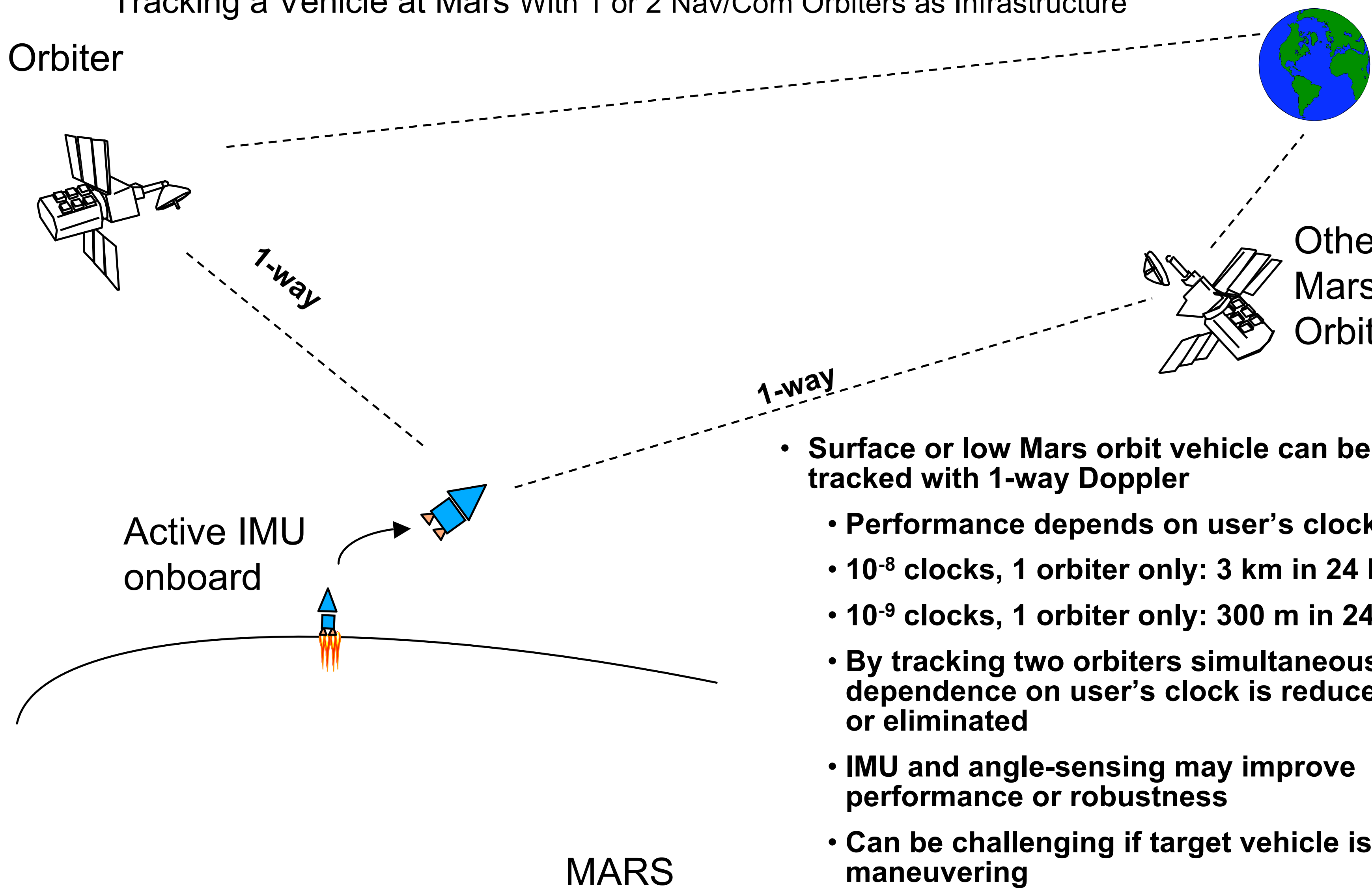




- **The MER mission dramatically proved the high value of having navigation & telecom "infrastructure" during challenging surface operations on other planetary bodies**
- **What is the best approach for Mars? For the Moon?**
  - **Light travel time to Mars is tens of min, but only about 1 sec to the Moon**
    - **Importance of autonomy**
  - **Some Earth-orbiting GPS can be usefully tracked at Moon**

Applications of Clocks to Space Navigation & "Planetary GPS"

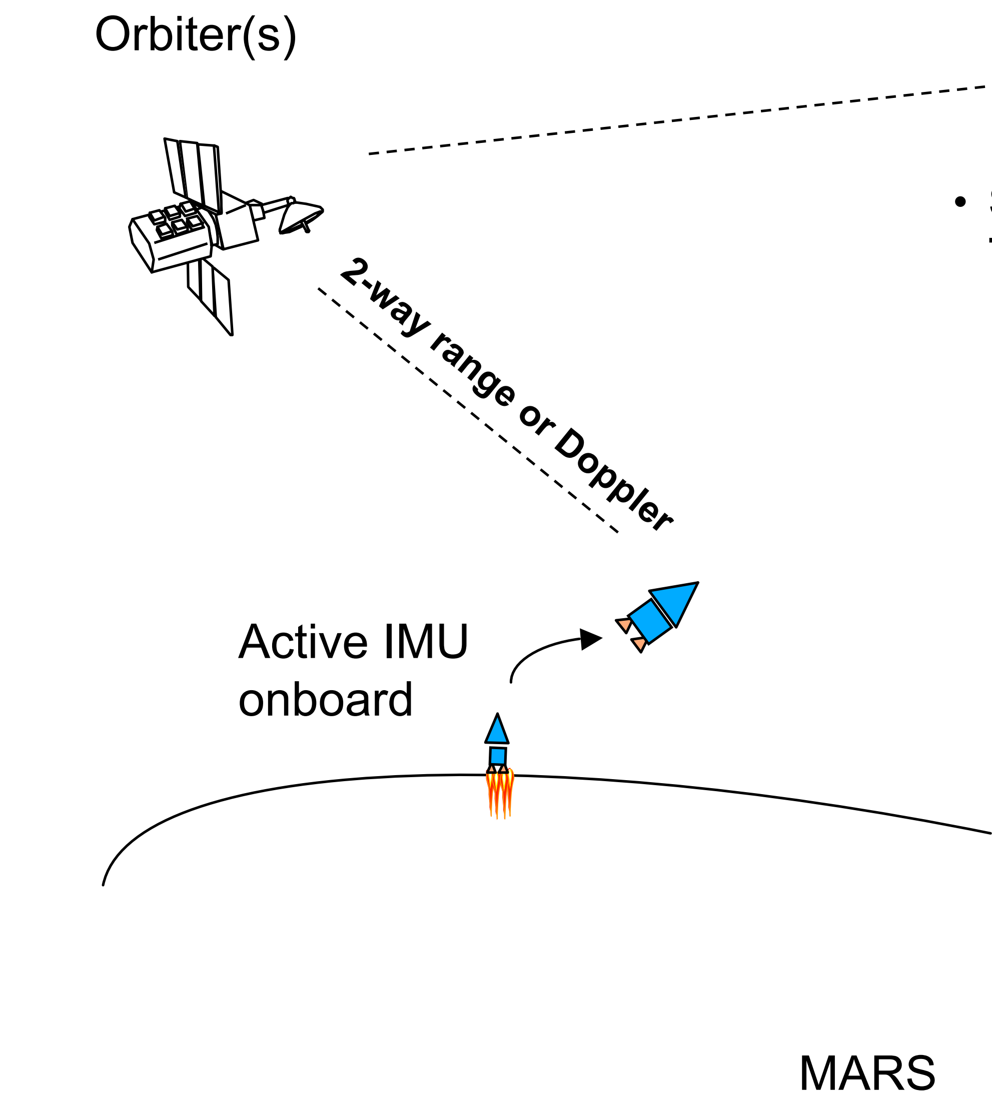
Tracking a Vehicle at Mars With 1 or 2 Nav/Com Orbiters as Infrastructure

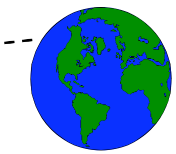


- **Surface or low Mars orbit vehicle can be tracked with 1-way Doppler**
  - **Performance depends on user's clock**
  - **10^{-8} clocks, 1 orbiter only: 3 km in 24 hrs**
  - **10^{-9} clocks, 1 orbiter only: 300 m in 24 hrs**
  - **By tracking two orbiters simultaneously, dependence on user's clock is reduced or eliminated**
  - **IMU and angle-sensing may improve performance or robustness**
  - **Can be challenging if target vehicle is maneuvering**

Applications of Clocks to Space Navigation & "Planetary GPS"

Tracking a Vehicle at Mars With 1 or 2 Nav/Com Orbiters as Infrastructure



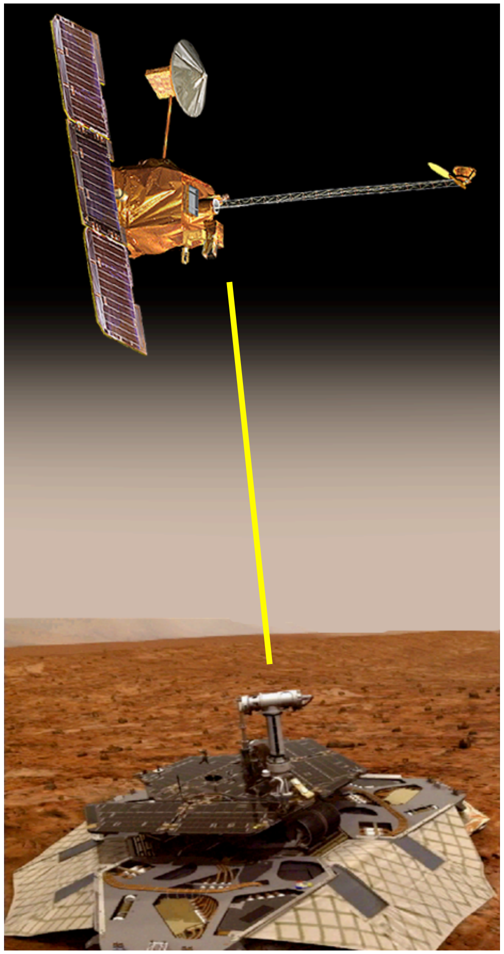


- **Surface or low Mars orbit vehicle can be tracked with 2-way data types**
  - **User does not need extremely good clock**
  - **< 100 m position accuracy in 24 hrs with just 1 tracker (orbiter)**
  - **Combination of 3 trackers (orbiters and/or ground) can provide real-time knowledge < 100 m**
  - **Incorporating angle-sensing and/or IMU data can reduce number of trackers**
  - **Can be challenging if target vehicle is maneuvering**

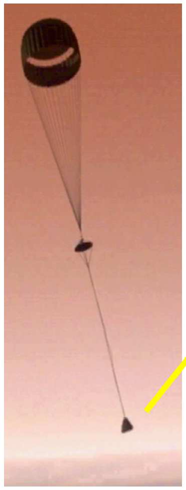
Applications of Clocks to Space Navigation & "Planetary GPS"

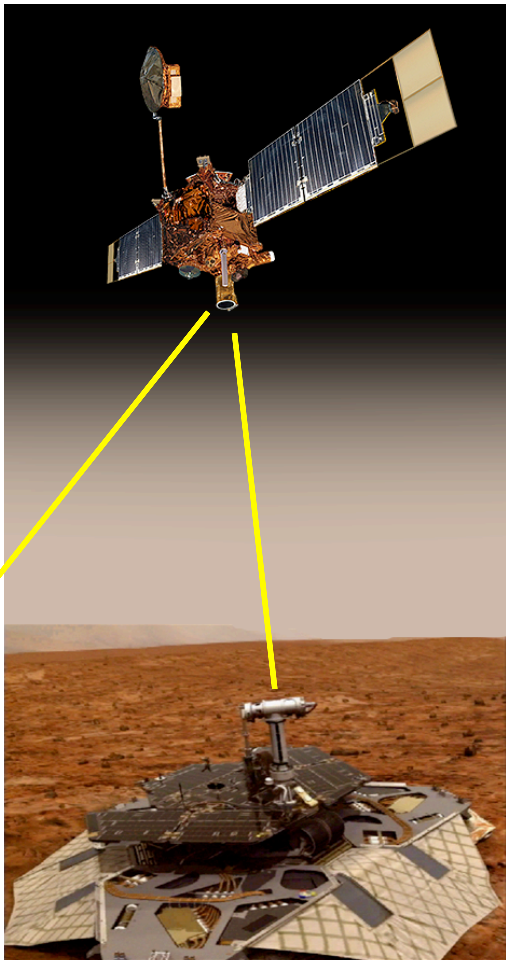
MER Tracking via Odyssey and MGS

- **Two-way Doppler tracking was successful between the landed MER and Odyssey. A position was eventually determined (days later) accurate to tens of meters.**



- **One-way Doppler tracking was successful between MER and MGS *during and after* the critical Entry/Descent/Landing.**





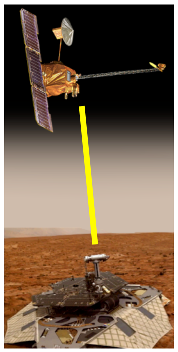
Applications of Clocks to Space Navigation & “Planetary GPS”

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes

1. **Rely on simpler data types such as 2-way or 1-way Doppler with “orbiters of opportunity,” i.e., existing orbiting vehicles (as was done with MER)**
2. **Deploy a sparser version of a GPS-like constellation. Provide Navigation services similar to how GPS does at Earth. Same space vehicles can also provide Telecommunications services.**
3. **Deploy constellation utilizing dual one-way tracking between infrastructure assets and users, which must be equipped with compatible navigation/telecom transceivers.**

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

1. Rely on simpler data types such as 2-way or 1-way Doppler with "orbiters of opportunity," i.e., existing orbiting vehicles (as was done with MER)



- Advantages
  - No new technology; uses whatever orbiters are there (lowers cost)
  - Good user space clocks not needed (lowers cost).
    - Typically, long-term orbiters carry USOs.
- Disadvantages
  - Poorer performance (tens of meters to kilometers after ~ days)
  - Real-time is not easily done with Doppler, since time history is needed to infer dynamics. Cannot easily track irregularly maneuvering vehicles.
  - Uses whatever orbiters are there -- not available on demand. Won't be immediately available for emergencies.

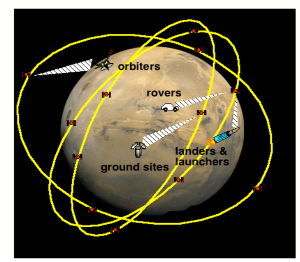
Applications of Clocks to Space Navigation & “Planetary GPS”

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

  2. Deploy a sparser version of a GPS-like constellation. Provide Navigation services similar to how GPS does at Earth. Same space vehicles can also provide Telecommunications services.

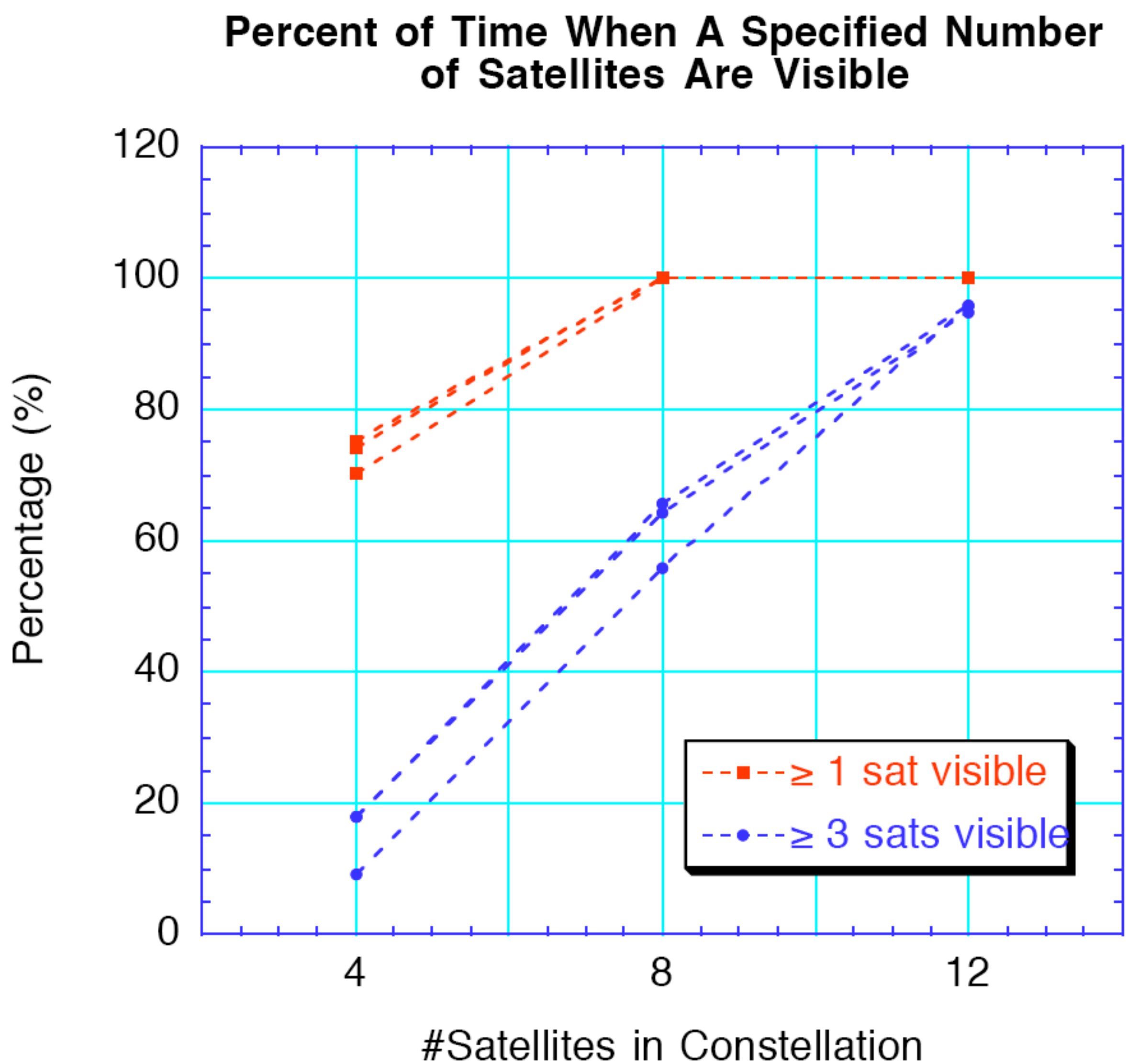
  - Advantages
    - High performance possible, depending on coverage/visibility and clock quality
    - Real-time emergency services possible
  - Disadvantages
    - Higher cost for operating infrastructure assets (dedicated constellation) at Moon or Mars
    - Higher cost and complexity for utilizing high quality space clocks (as with GPS)

– Technology challenges …



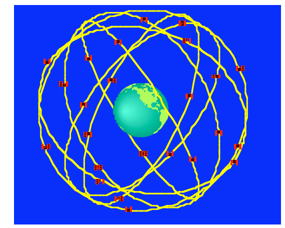
- Availability/coverage determined by sparseness of constellation
- Small, cheap very stable space clocks to deploy on infrastructure and users
  - Combination of better clocks + IMU can compensate for coverage “gaps”
- Develop a cost effective concept of operations.
  - Key trade: should ground tracking terminals be remotely deployed (as are used for GPS operations)? If so, should they be equipped with highly stable clocks? How long can/will such ground automated ground terminals function in a hostile environment? Can the system be maintained solely via Earth tracking? How would the reference frame tie be maintained?

- Results of a simulation performed to evaluate tracking coverage for a Mars network of low-altitude orbiters



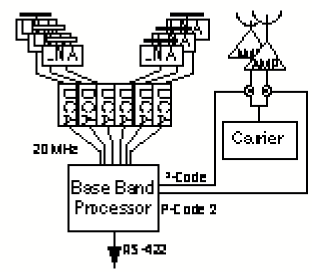
Applications of Clocks to Space Navigation & "Planetary GPS"

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

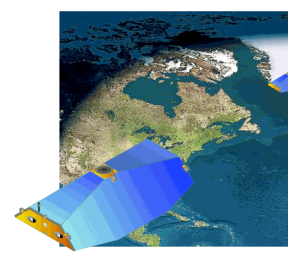


3. **Deploy constellation utilizing dual one-way tracking between infrastructure assets and users, which must be equipped with compatible navigation/telecom transceivers.**
   - Advantages
     - Real-time high (sub-meter) accuracy (if coverage is adequate)
     - Smaller number of good space clocks needed because system relies on dual-one-way tracking data (insensitive to clocks)
   - Disadvantages
     - Self-jamming (transceivers transmitting and receiving simultaneously)
     - System complexity for scalability to many simultaneous vehicles/users
     - Users must carry compatible transceivers
   - Role of clocks
     - Good clocks not required for precise ranging between spacecraft, but at least one to several long-term stable and precise space clocks are required to maintain system timing and reference frame registration (equivalent to knowledge of UT1-UTC at Earth).
     - Without these stable clocks, system autonomy will not be possible and system operation will be more complex and costlier

Advanced GPS flight receivers for Earth, atmospheric, and ocean science and for precise navigation.



Autonomous Formation Flyer (AFF) and Software Reconfigurable Radio/Transceivers for integrated deep-space navigation/telecom and formation flying.



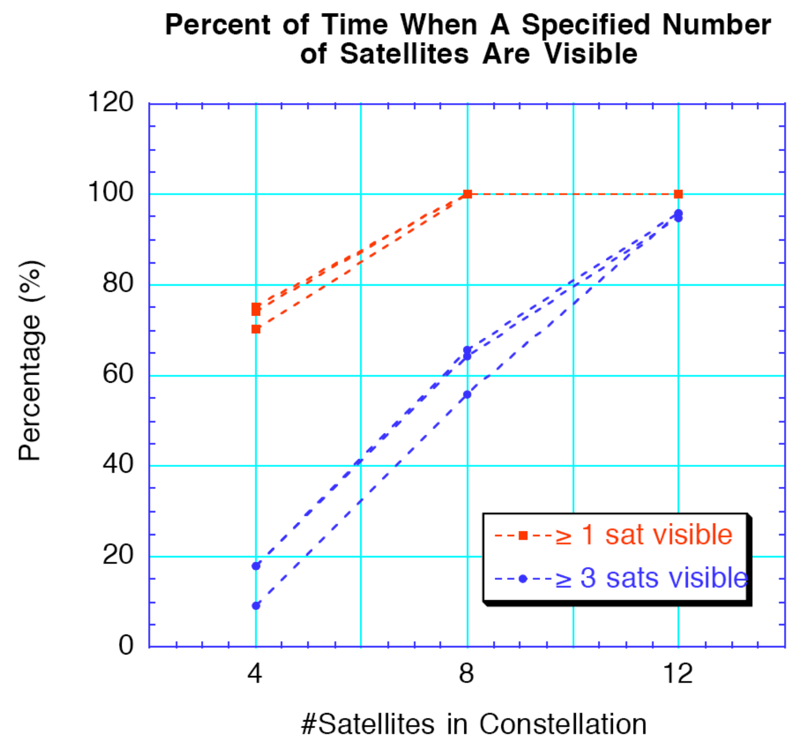
GRACE combines space GPS plus ultra-precise (1-micron delta-range) inter-spacecraft transceivers

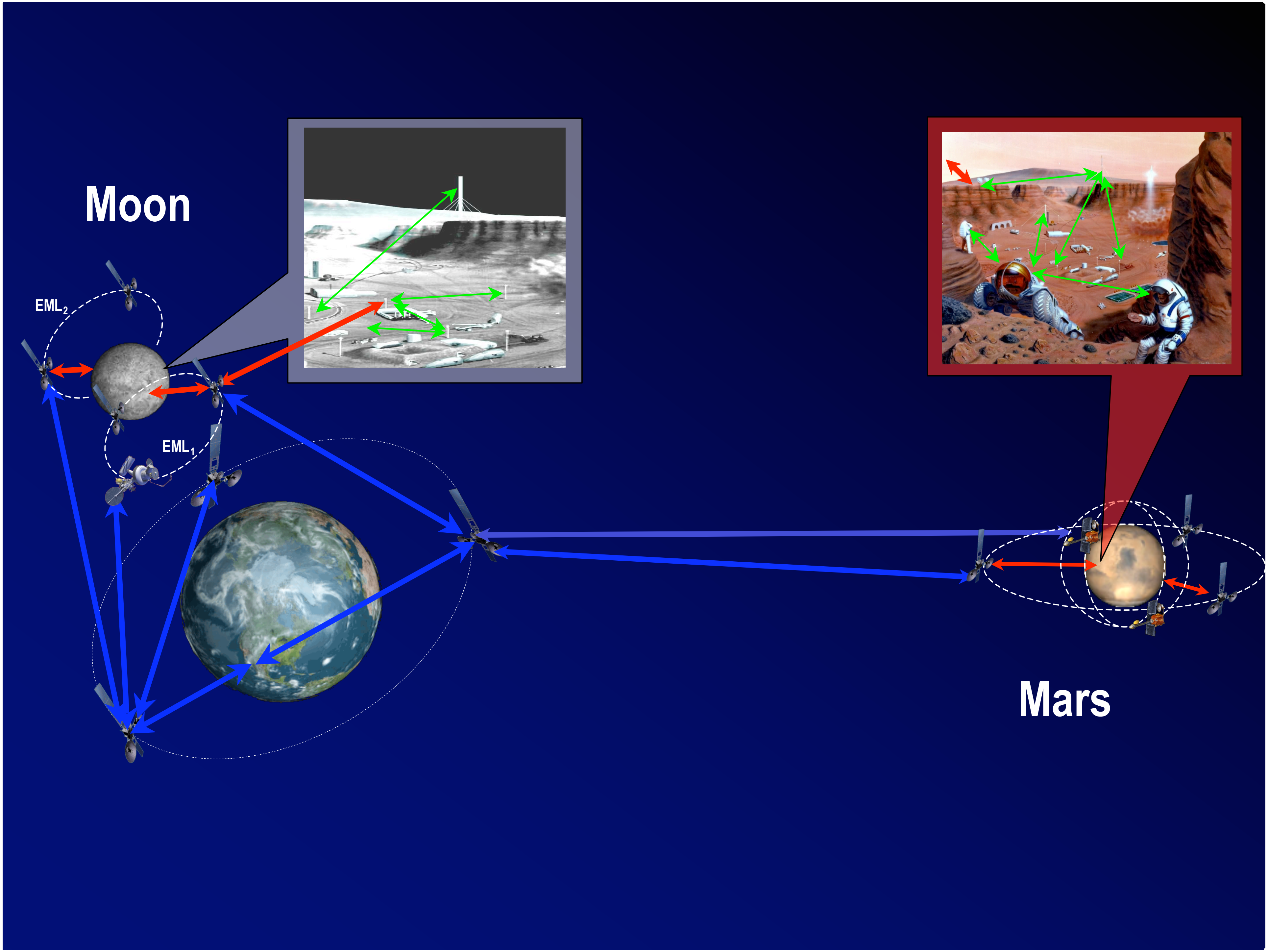
Applications of Clocks to Space Navigation & "Planetary GPS"
Summary

- The ability to fly atomic clocks on GPS satellites has profoundly defined the capabilities and limitations of GPS in near-Earth applications
- It is likely that future infrastructure for Lunar and Mars applications will be constrained by financial factors
- The development of a low cost, small, high performance space clock -- or ultra-high performance space clocks -- could revolutionize and drive the entire approach to GPS-like systems at the Moon (or Mars), and possibly even change the future of GPS at Earth
- Many system trade studies are required. The performance of future GPS-like tracking systems at the Moon or Mars will depend critically on clock performance, availability of inertial sensors, and constellation coverage.
  - Example: present-day GPS carry 10^{-13} clocks and require several updates per day. With 10^{-15} clocks, a constellation at Mars could operate autonomously with updates just once per month.
- Use of GPS tracking at the Moon should be evaluated in a technical study.

- **Next steps:** Develop a program to perform simulations and experiments to evaluate and compare capabilities and costs for the different navigation/telecom scenarios for Moon and Mars infrastructure

- Determine how precise/stable flight clocks and IMU sensors can "fill in" coverage gaps for sparser versions of GPS
  - Goal is to determine how GPS-like capabilities can be enabled with fewer than 4 "GPS" in view
    - How long and how accurately can positioning be sustained with 3, 2, 1 or even 0 orbiters in view?
  - Use current GPS terrestrial and space data to perform tests and experiments. Excellent data sets and test facilities are available.
    - Evaluate clocks and IMU sensors over a wide range of performance
  - Evaluate different concepts of operations
    - What is the value of an extremely accurate ground clock at Mars or Moon? How survivable is a ground clock, versus a space clock in an orbiter? Does the ground clock enable simplification of the orbiting payloads? Is the trade worthwhile?
- Evaluate GPS tracking at the Moon and how coverage might be extended to the far side




Moon
EML2
EML1
Mars

ATOMIC CLOCK REQUIREMENTS FOR PRECISE INTERPLANETARY NAVIGATION

Kurt Gibble, The Pennsylvania State University,
University Park, PA

ABSTRACT

Navigation is one of the best known applications for atomic clocks. On earth, the atomic clocks in the GPS provide meter level accuracies. Space based atomic clocks could provide GPS type precision for interplanetary navigation. I will describe a possible system using very good clocks in orbit around the earth, some of the considerations, and the requirements for the clocks.

OVERVIEW

The accuracies and stabilities of laboratory atomic clocks have surpassed 1 part in 10^{15}. A number of clock experiments, PARCS, RACE, and ACES, were slated to fly on the ISS. All three aimed for high accuracy and stability; RACE's stability goal was 3×10^{-15} for one second of averaging. The accuracy of these clocks will support high precision interplanetary navigation.

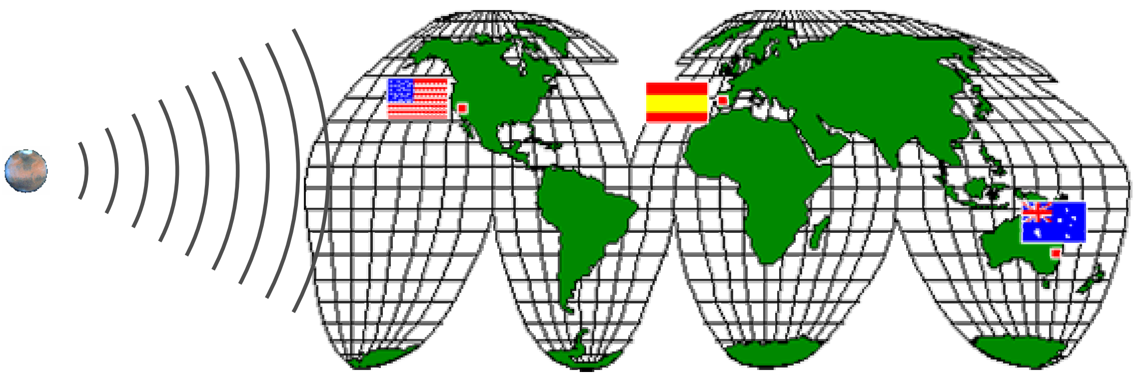
One can imagine a variety of schemes to navigate to other planets that take advantage of atomic clocks. One limit is to construct a GPS type system around the planet of interest. For such a system, because the clock ranges to the planet are short, the clock performances can be modest and therefore the clocks can be relatively small. Another limit of the spectrum is to construct a system around the earth. For such a system, the clock performance must be much better due to the long range to the planet of interest. While these clocks are also larger, they must only be launched to an orbit around the earth. In this paper, we lay out the possible performance of such a system of very good clocks orbiting the earth.

We consider clocks such as PARCS and RACE in a nearly geosynchronous orbit around the earth. With this baseline, a clock stability of 1×10^{-14} implies a transverse position uncertainty at Mars of 10 meters, comparable to GPS on earth. The range from the clock to the receiver can be better known using the two-way communication time delay.

The system should have rapid position updates with little time lag. It is therefore essential that the clocks transmit their position and time, as in GPS, so that the receiver can calculate its position. For the range, after an initial two-way link, GPS carrier phase techniques can be used for range updates without data latency. The clocks are intrinsically stable and a receiver on the planet of interest, such as Mars, can be used to measure the clock offsets at a known position. To precisely measure small time differences, the atomic clocks will have to be in orbit to avoid uncertainties due to propagation delays in the earth's atmosphere. One source of systematic position error is propagation delays in the Martian atmosphere. Because both clocks have an angular separation of hundreds of microradians, the propagation delay from both clocks will be largely common. Such a system needs to be augmented with inertial navigation when on the occluded side of the planet.

PENNSTATE

NASA DSN (Deep Space Network)



3 sites: Goldstone, Canberra, & Madrid.

24 m to 70 m radio telescopes.

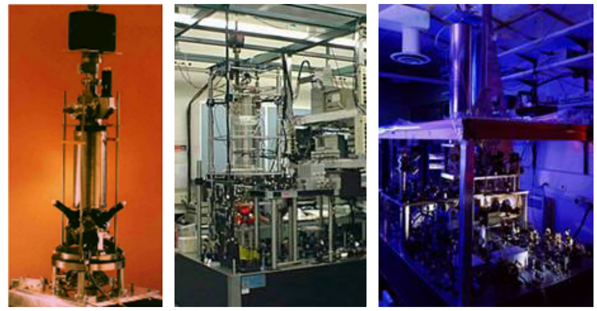
Uses the most stable & fieldable clocks.

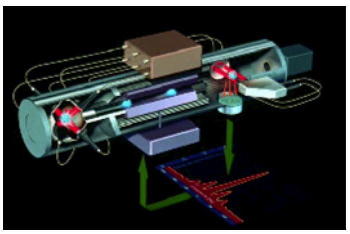
Different atmospheric delays.

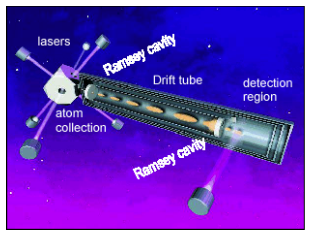
Better Clocks = Better Navigation?

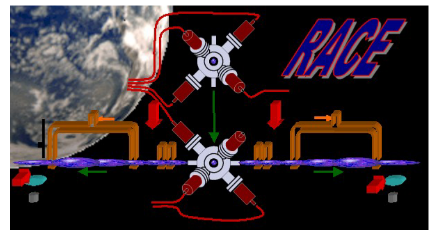
Many laser-cooled clocks have stabilities of 10^{-15}.

ACES, PARCS, & RACE: space-based clocks can be much better.

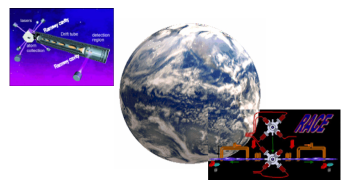




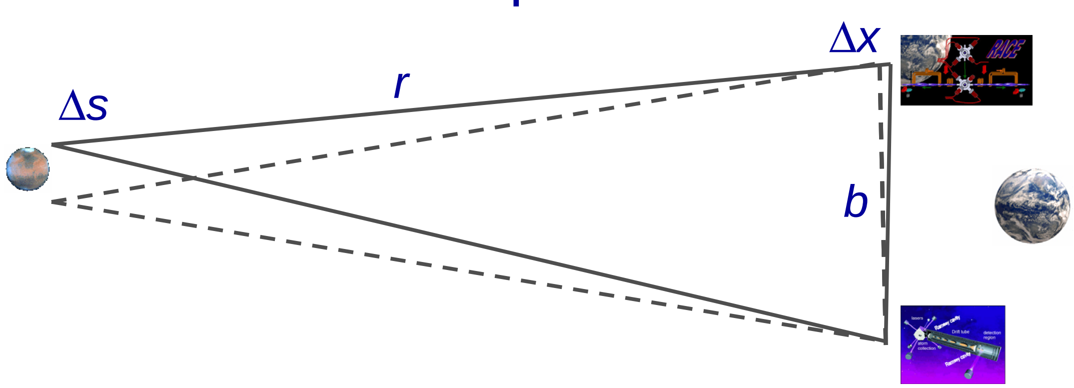




Really good clocks orbiting earth?



Resolution of a Space-Based DSN



Initial range comes from 2-way.

Different than GPS.

Geometry is very different.

Precise timing allows <10 m error.

Time differences are key.

Differential relative to a Mars station.

Geo Synch orbit

10 m @ Mars

$$dx = b\Delta\theta = \frac{b\Delta s}{r} = 2.5mm$$

$$\frac{\Delta x}{r} = \frac{\Delta f}{f} = 1.4\times10^{-14}$$

$$\Delta t = c\Delta x = 8.5ps$$

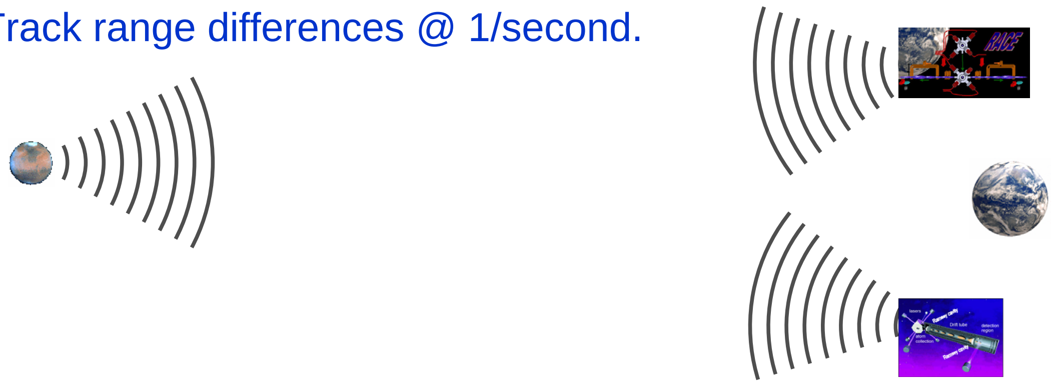
What Could a System Be?

Update rate should be ≈1/second.

DSN is limited to 8 to 42 min.

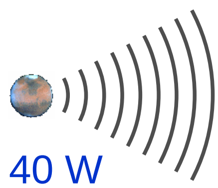
Receiver onboard vehicle.

Track range differences @ 1/second.



Microwave Signal on Optical Carrier

Cumbersome to build a 70 m radio telescope in space.



For scale, GPS satellites radiate 40 W over the earth.

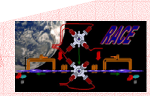
Optical carrier

1 cm “telescope” aperture is required for GPS radius at earth-Mars distance.

DSN is going optical.

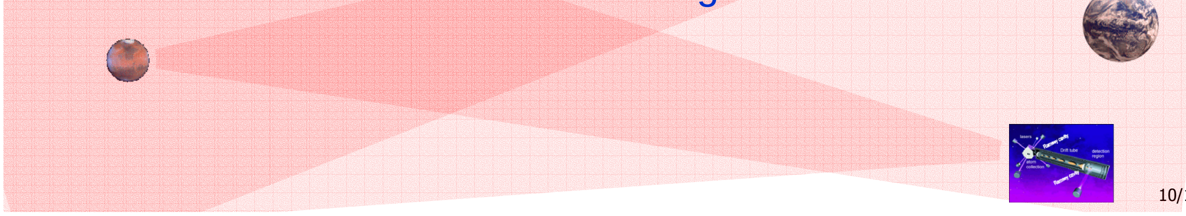
With 20 cm telescope →1 W of power?

Track planet



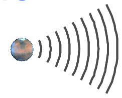
Mars atmosphere?

Dark side is occluded – inertial navigation.

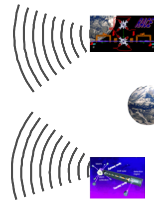


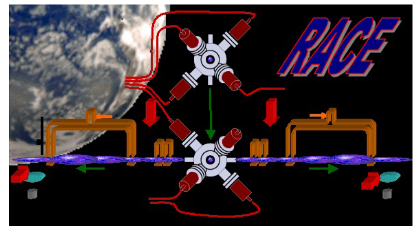
Summary

- Better clocks can give better navigation.
  - Many small & good clocks @ mars
  - Really good clocks near earth



- We've done the clock science.
- It'd be great to fully implement in space.
  - RACE goal was 3×10^{-15} stability @ 1s.
  - <10 m @ Mars from earth.
  - Small telescopes
  - Low power
  - Fast update rates





Small Mercury Ion Clock for On-board Spacecraft Navigation*

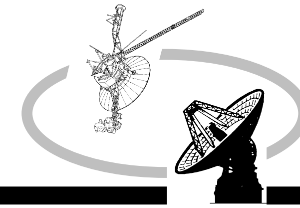
John D. Prestage, Sang Chung, Thanh Le, R. Hamell,
Lute Maleki, Robert Tjoelker
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

***Research performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration**

Outline

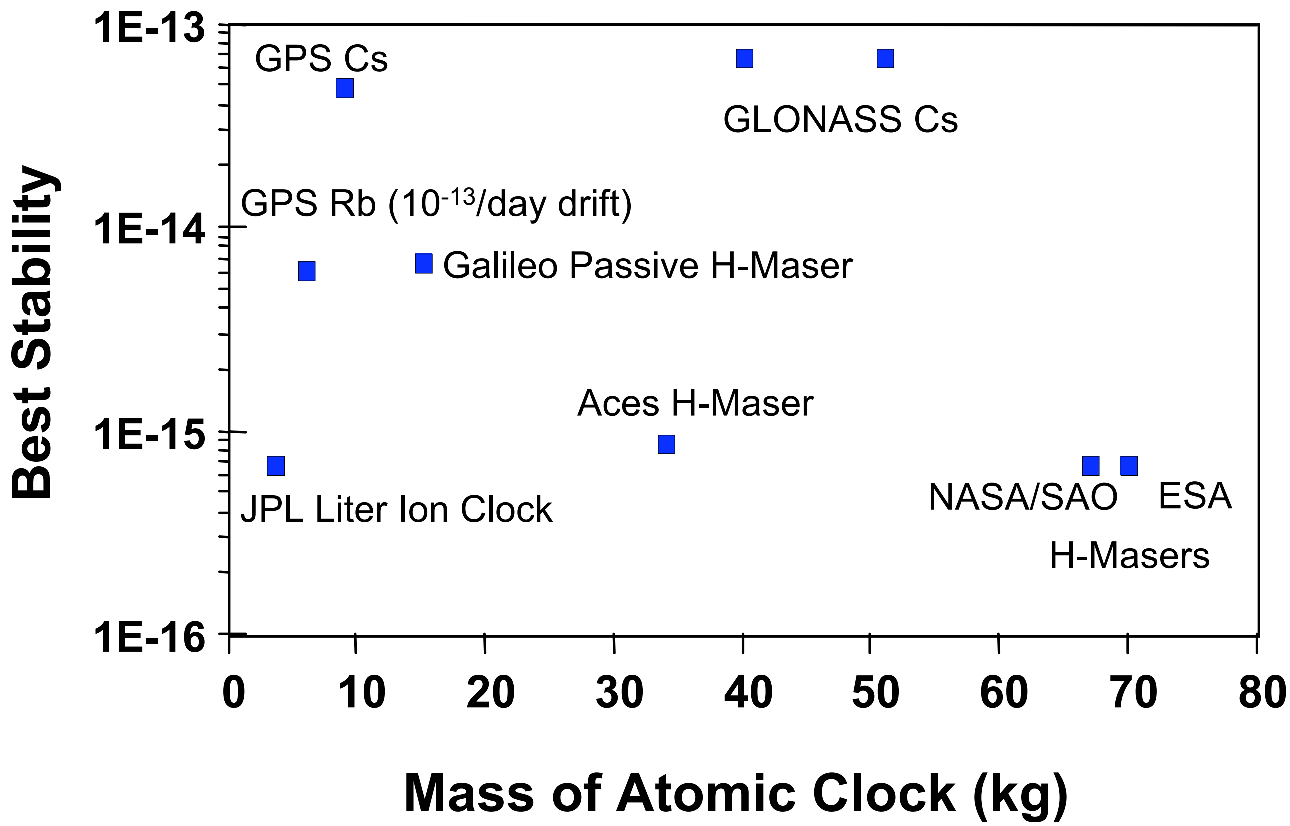
- Review of Ultra-Stable Space clock Mass vs Stability
- Laboratory Hg microwave Ion clock
  - Ion shuttling from ‘Optical’ trap to Microwave resonance trap;
  - $3x10^{-16}$ ‘floor’ with > 100x less drift than space Rb;
- Development of a One-Liter Hg Ion clock
  - Optical System Re-design;
  - Trap miniaturization, one piece brazed, no fasteners,…
  - Ultra-high Vacuum developed for getter pumping;
- Tests of Breadboard Liter clock Package
  - $5x10^{-14}$ at 1 second;
  - 3x reduction buffer gas shift with Neon
- Summary

Small Mercury Ion Clock for On-board Spacecraft Navigation



- JPL can use a small, reliable, high stability clock, ~10^{-14} to 10^{-15} for deep space navigation
- Interplanetary S/C radio system components (TWTA, USO,..) are 1-2 kg /2-3 liters

Space-Based Clocks (LEO)

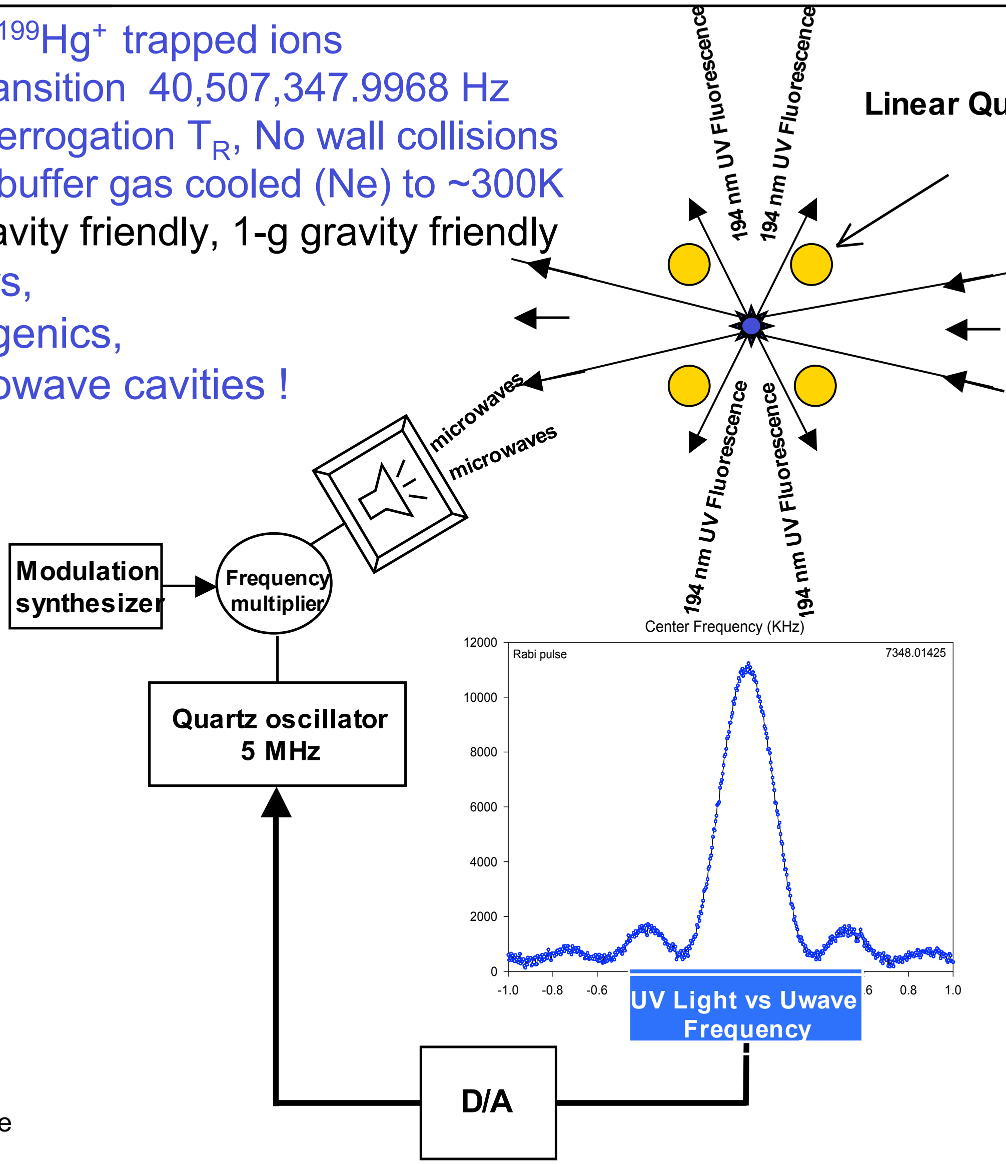


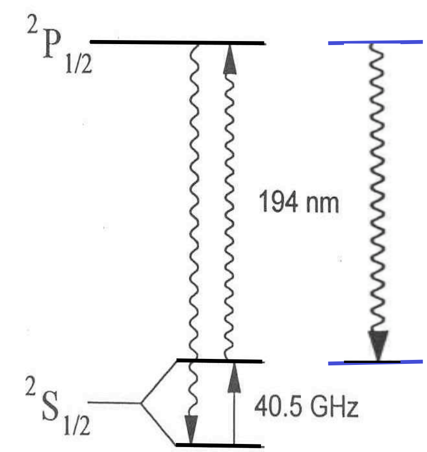
How Large are Deep Space Craft ?

Voyager I	< 825 kg
Magellan (1989)	1035 kg
Ulysses (1990)	370 kg
Mars Observer ☹	1018 kg
Mars Global Surveyor	674 kg
Mars Pathfinder	570 kg
Cassini (1997)	2580 kg
Deep Space 1	373 kg
Mars Climate Orbiter ☹	388 kg
Stardust (1999)	300 kg
Mars Odyssey	376 kg
MER (Rover 185kg)	1013 kg (rover + s/c)

Why/How a Clock from Ions ?

- 10^6-10^7 $^{199}Hg^+$ trapped ions
- Clock Transition 40,507,347.9968 Hz
- Long Interrogation T_R, No wall collisions
- Ions are buffer gas cooled (Ne) to ~300K
- Micro-gravity friendly, 1-g gravity friendly
- No lasers,
- No cryogenics,
- No microwave cavities !





^{199}Hg 'Clock' Ion 194 nm scattered light	^{202}Hg 'Lamp' Ion 194 nm emission

- Optical Pumping: 194 nm UV
- $^{202}Hg^+$ RF discharge lamp
- Q~3×10^{11} resonance measured thru UV fluorescence

Over-view of Multi-pole Clock (1st design)

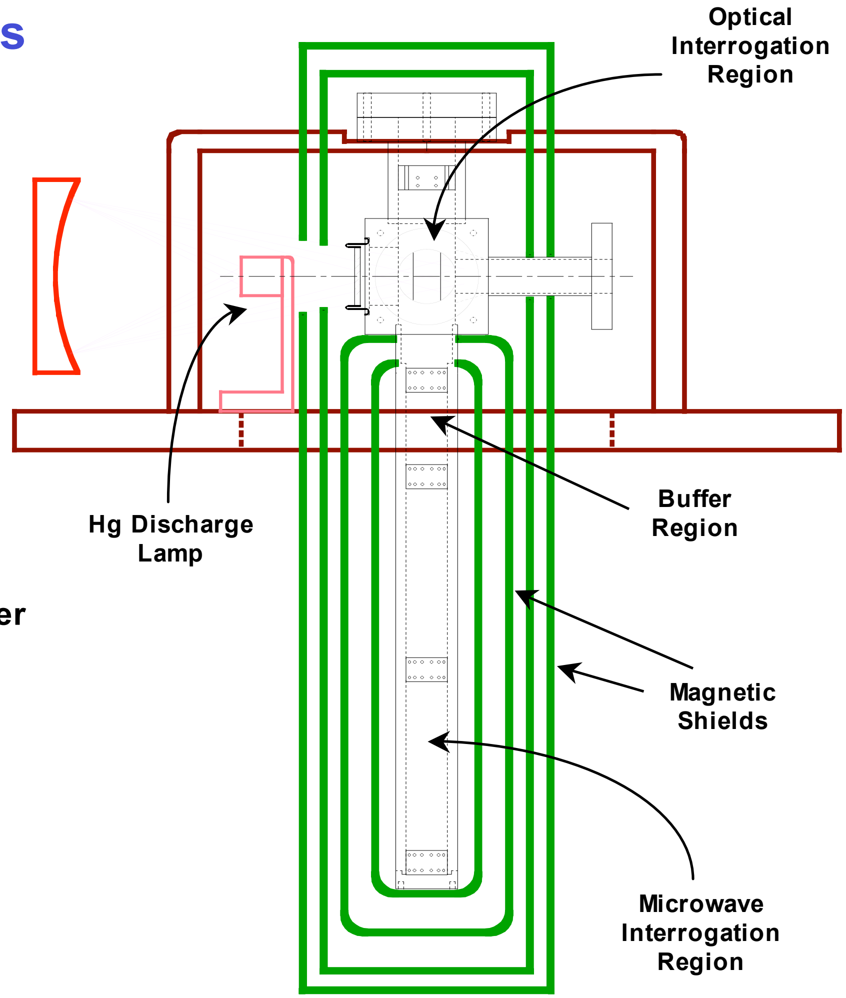
No Lasers, Microwave Cavities, or Cryogenics

~20 years operational experience in 5 clocks,
- 3 linear traps,
- 2 shuttle from linear 4-pole to multi-pole
- All exceed 10^{-15} stability

Ions are Optically Pumped in a quadrupole trap
(optically open and ions are concentrated)

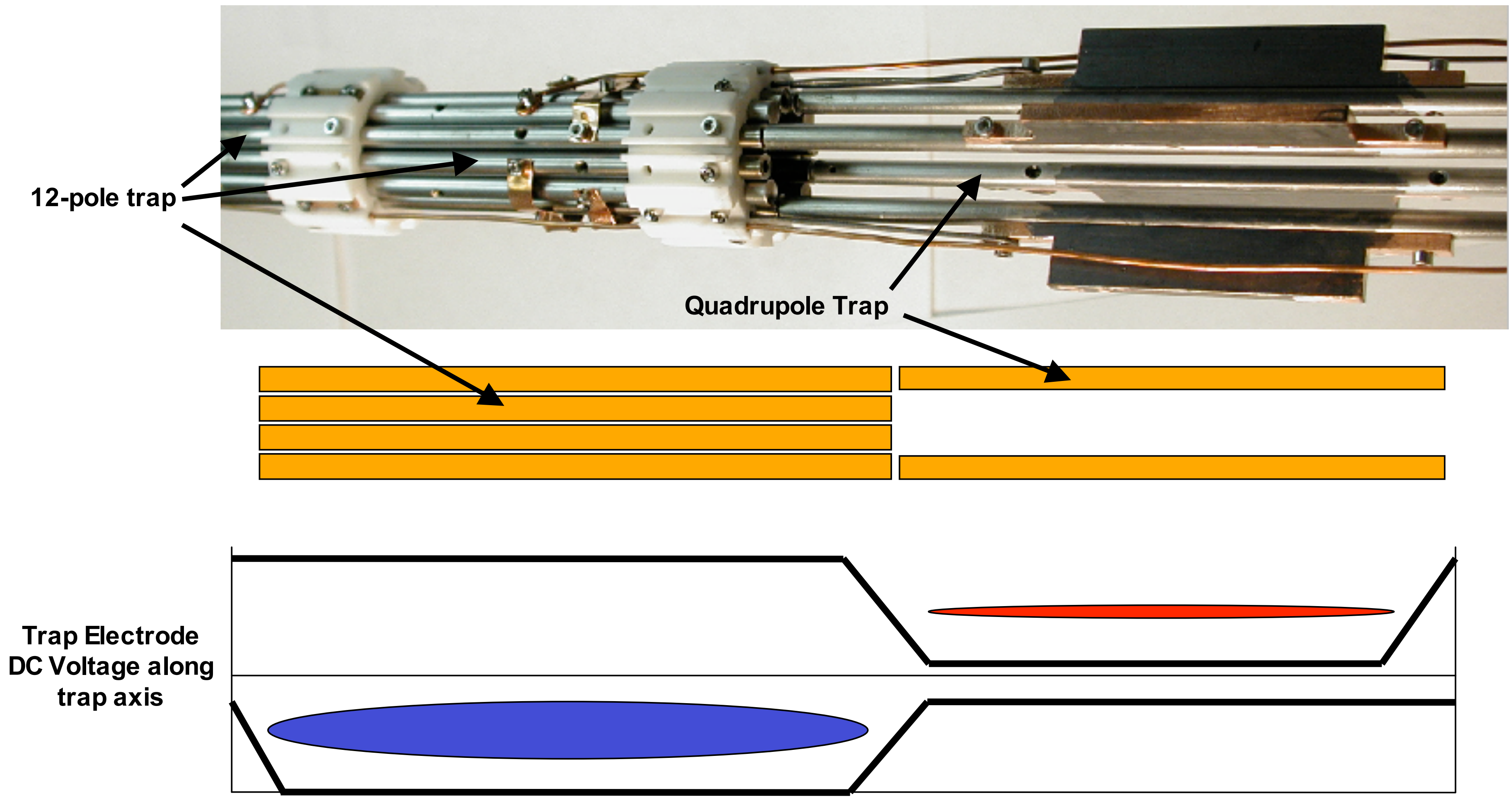
40 Ghz Clock resonance in Multi-Pole trap, an RF trap with little or no radio frequency micromotion
- (low ion density, low micro-motion, little space-charge number sensitivity)
- Doppler-free for transverse k vector
- Doppler broadened for axial k vector

Ions are shuttled between 4-pole and 12-pole



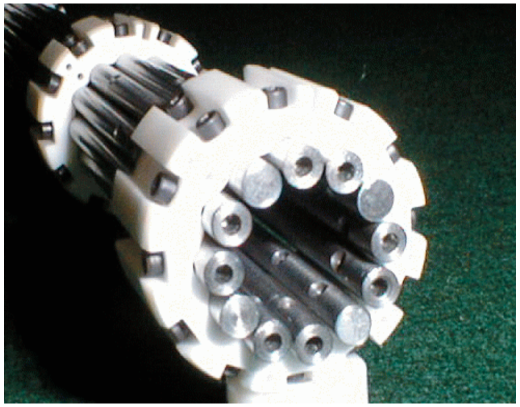
Hg Ion Frequency Standard

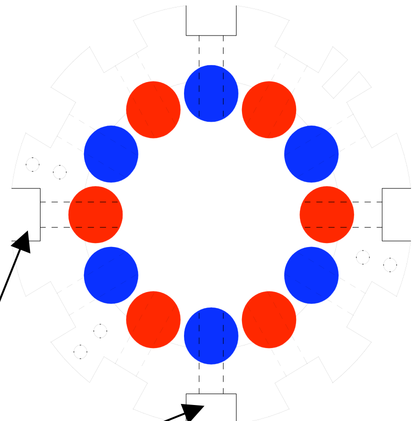
Shuttling Ions from Quadrupole to 12-Pole (and back)

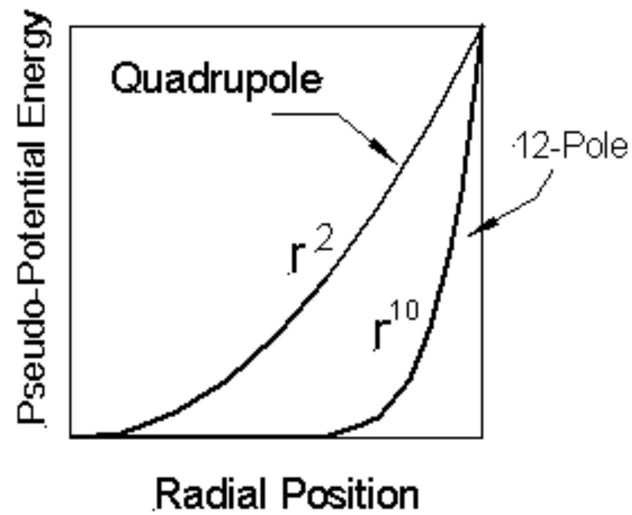


~5,000,000 shuttles have been executed to date in USNO unit

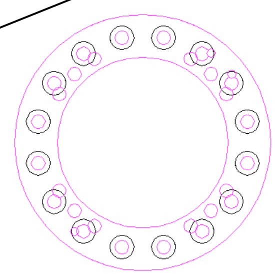
Quadrupole vs Higher Pole
(RF trap with little micro-motion in microwave region)







Laboratory 12-pole



Space-clock 16-pole
60% external diameter
100% internal diameter

Pseudo-potential grows as R^{2k-2} for 2k rod electrodes

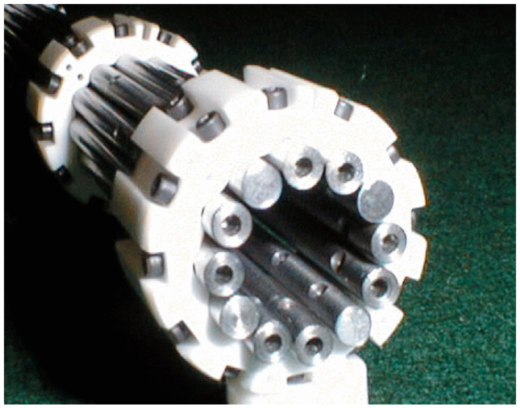
$$U_{pseudo} \propto R^{2k-2} \qquad \overline{KE}_{transverse} = (k-1)\overline{U}_{pseudo}$$

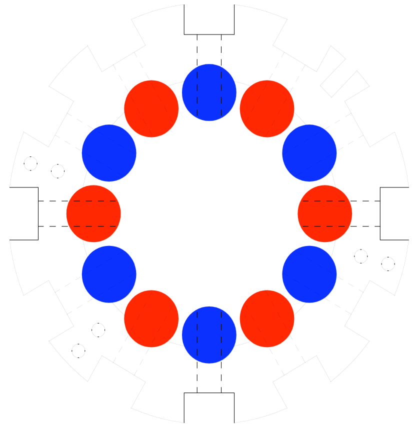
(Virial Theorem)

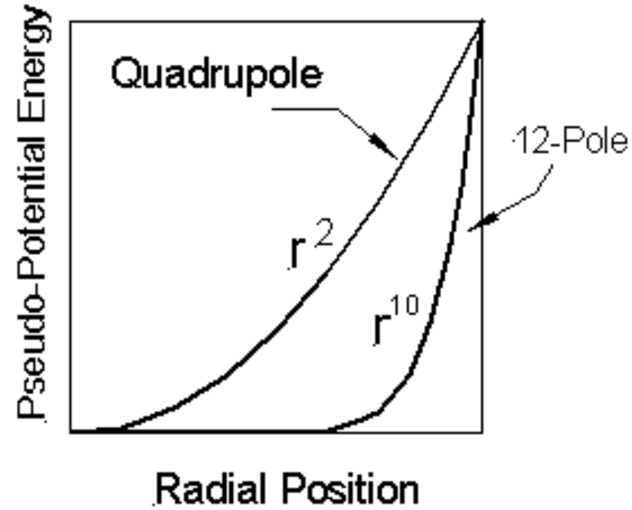
$$\overline{KE}_{m-motion} = \overline{U}_{pseudo} = \overline{KE}_{tranverse} \big/ (k-1)$$

RF Trap with very little RF micro-motion (k=2 quadrupole)

Quadrupole vs Higher Pole (Well Depth)







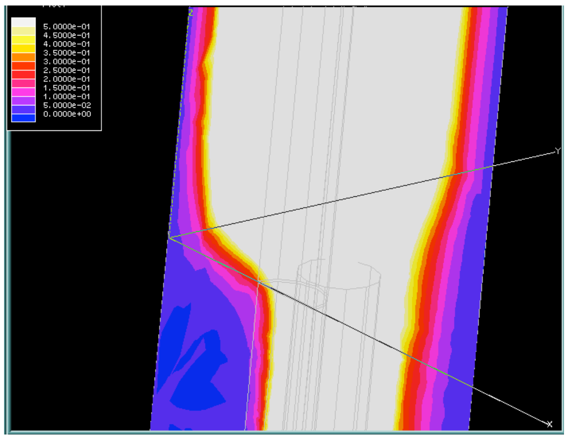
$$\eta = \frac{2q\left|\nabla E_0\right|}{m\Omega^2} = k(k-1)\frac{qU_0}{m\Omega^2 r_0^{\,2}}\hat{r}^{k-2} \leq 0.3 \equiv \eta_{\max}$$

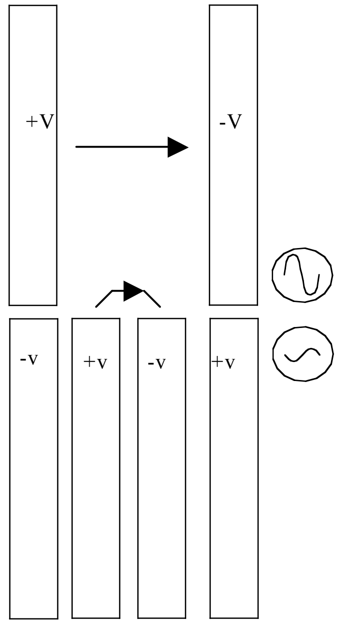
Numerical trajectory;D. Gerlich, Adv. Chem. Phys. LXXXII (1992)

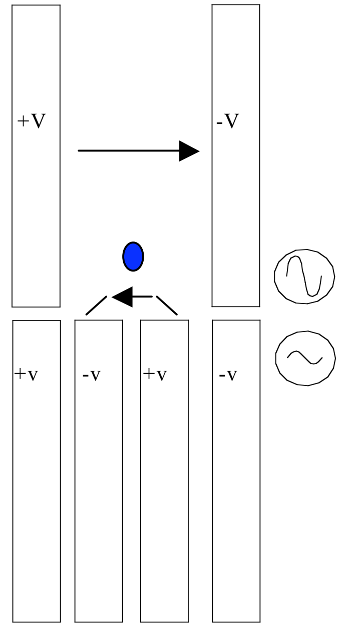
$$V^*_{k>>1}(R_{\max}) = \frac{m\Omega^2 r_0^{\,2}}{k^2}\frac{\eta_{\max}^{\,2}}{16}$$

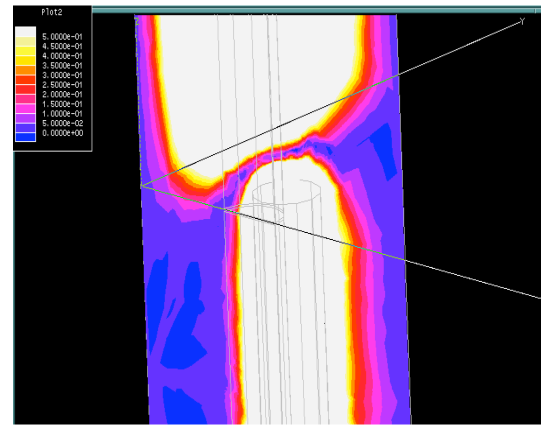
Well depth diminishes with k^2 unless frequency, Ω, increases with k

Shuttling Ions from Quadrupole to 12-Pole (phase must change on co-linear rods at trap junction)









Opposite Phase on colinear electrodes produces good RF pseudopotential

Same Phase on colinear electrodes produces a hole in the RF pseudopotential

- **Problem: Joining a 4-pole to an arbitrary k-pole microwave resonance trap. Holes in the pseudo-potential cannot be avoided.**
  - **Can't use the higher pole traps where the lowest micro-motion is achieved.**

•Solution:

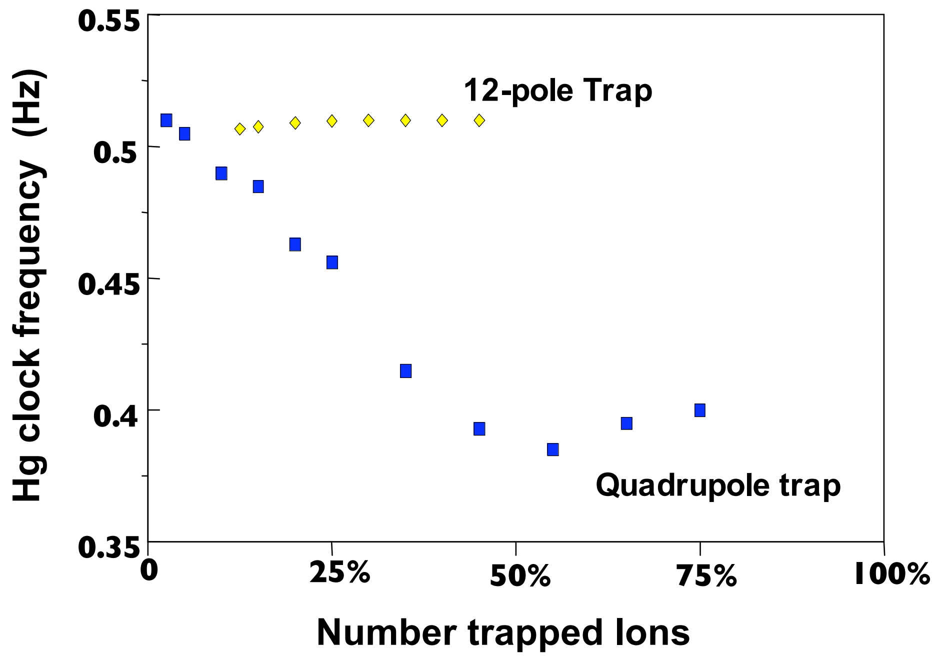
Operate the Higher pole trap at different frequency (e.g., ~2x higher). Holes open and close faster than ions can drift through.

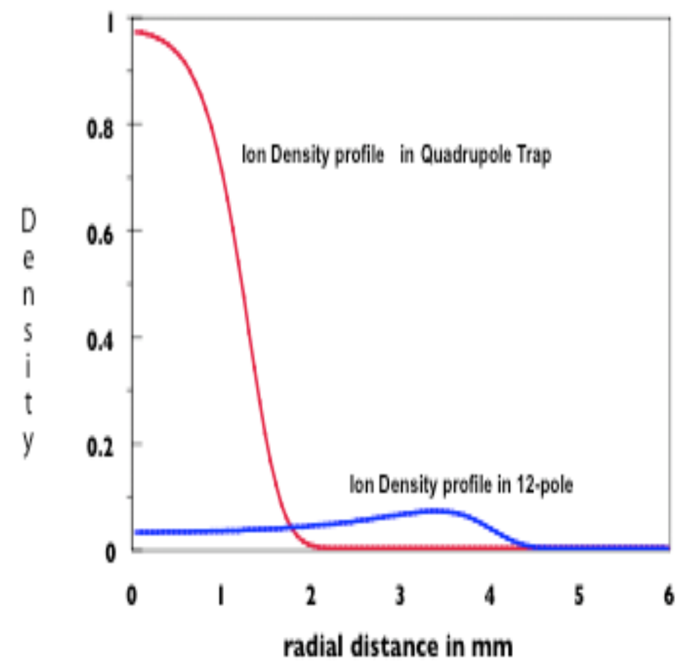
Well depth ~ $\frac{\Omega^2}{k^2}$ **can be preserved as k gets large.**

Ion-number sensitivity is drastically reduced

Ion-number frequency pulling is at least 20x reduced from LITS quadrupole !

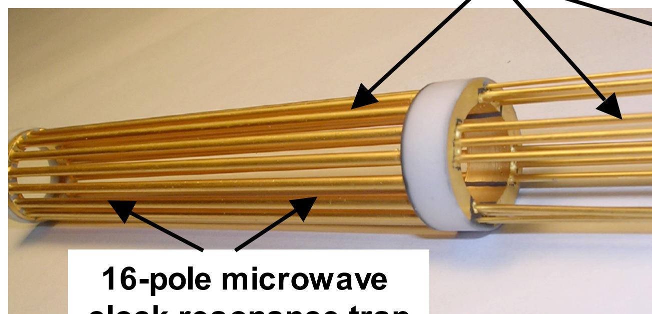
It doesn't behave like ion heating and 2nd-order Doppler frequency pulling !

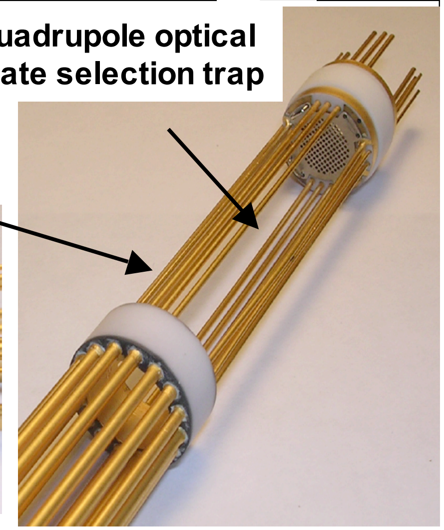


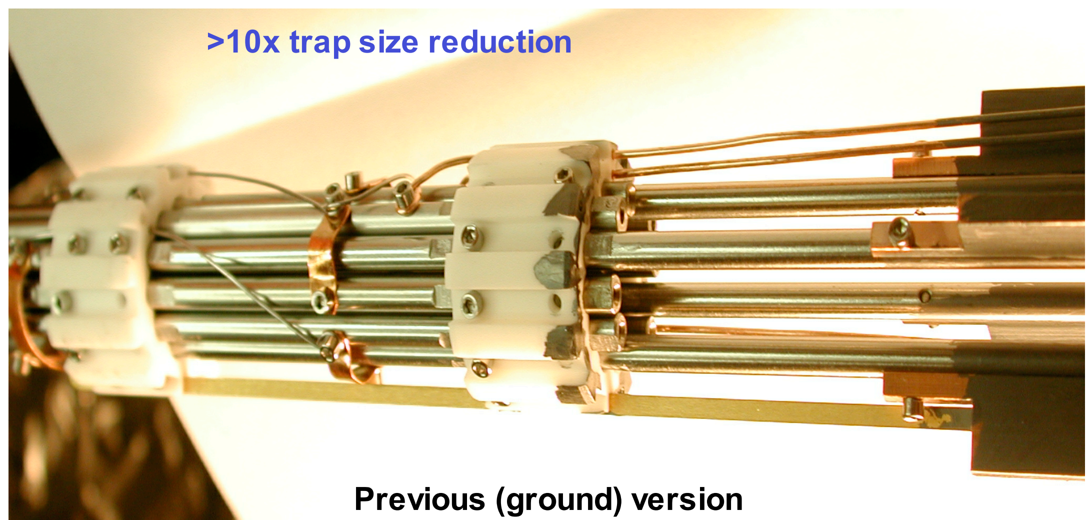


Miniaturizing Ion Traps

- State selection/optical interrogation in quadrupole; microwave clock resonance in higher multipole trap.
- Ion traps are brazed, “one piece” with metallized electrical inter-connects; no screws, etc. used as fasteners.
- Non-magnetic parts required for high Q atomic resonance ($Q \sim 3 \times 10^{11}$).
- 16-pole provides better isolation to stray external fields, for 0.056” moly rod size.
- 4-pole load trap has twice the well depth of the previous version; better ion load rates, higher SNR in clock resonance.



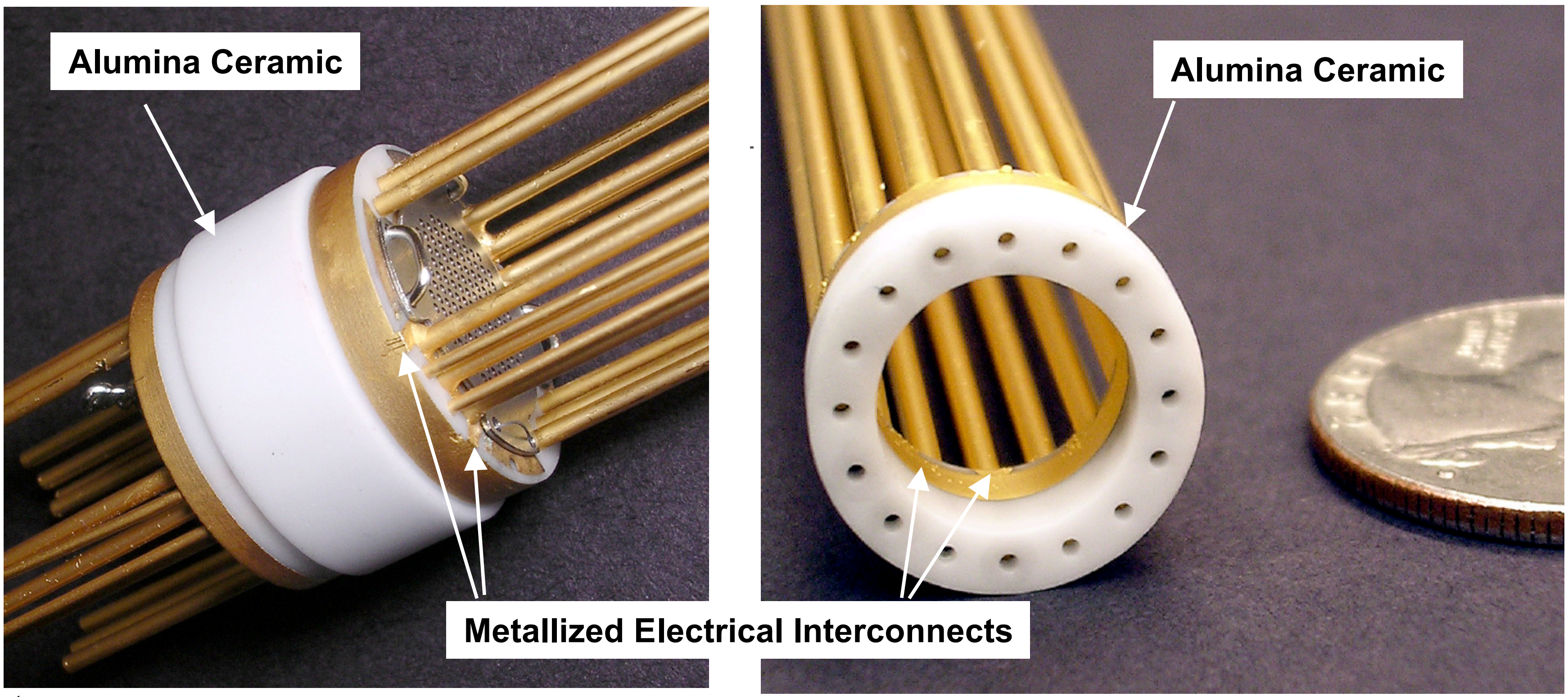




John Prestage

Full Trap Design, Fabrication Completed

- 4 trap assemblies procured and delivered, 5th to be inspected for electrical connection integrity;
  - **First 2 assemblies were "learning curve" fabrications, mechanical/magnetic/electrical problems**
  - **Remaining 3 are ready for clock tests.**



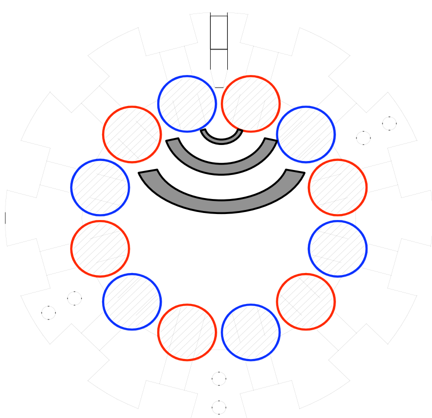
John Prestage

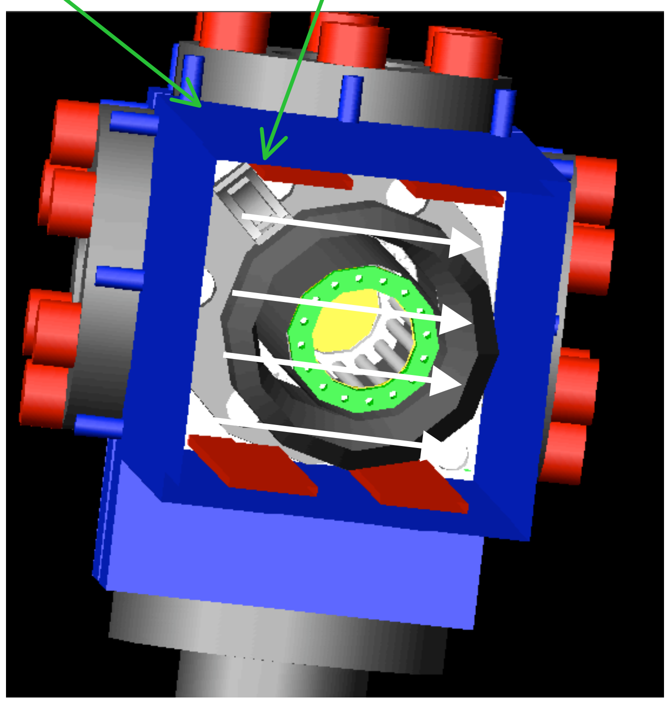
Physics Package Assembly

Inner Shields, field coils, and WR-19 waveguide

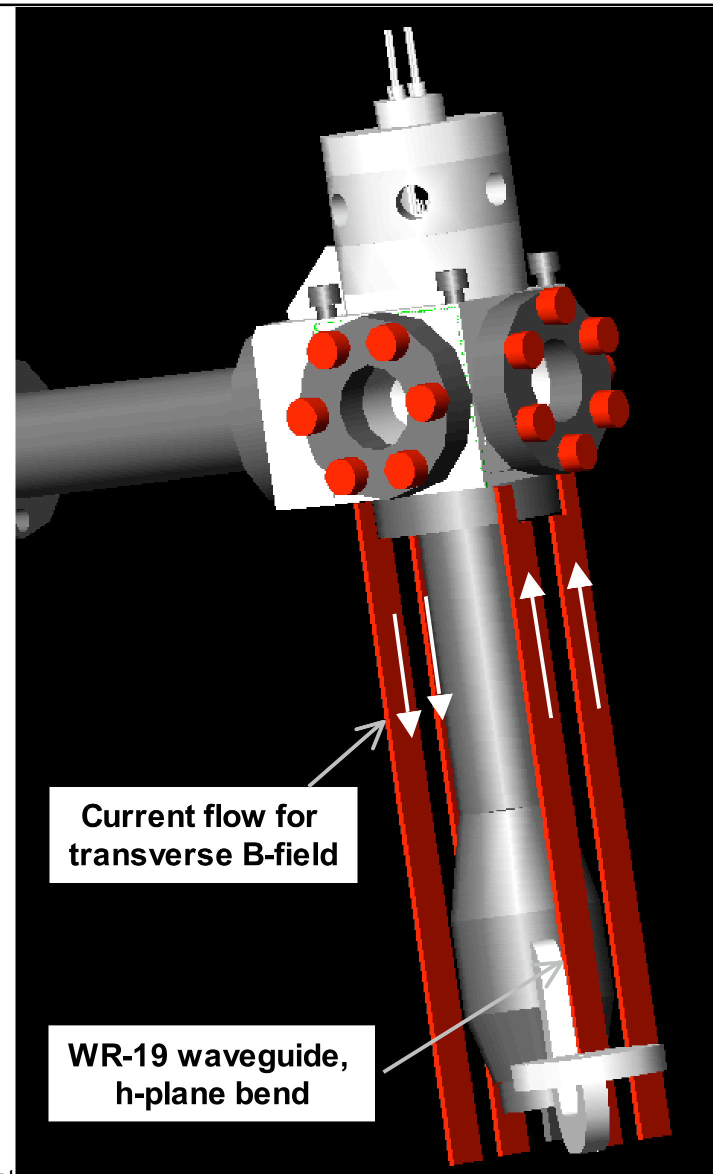
Inner magnetic shield square cross-section

Microwaves propagated trap axis avoids carrier suppression of 40.5 GHz



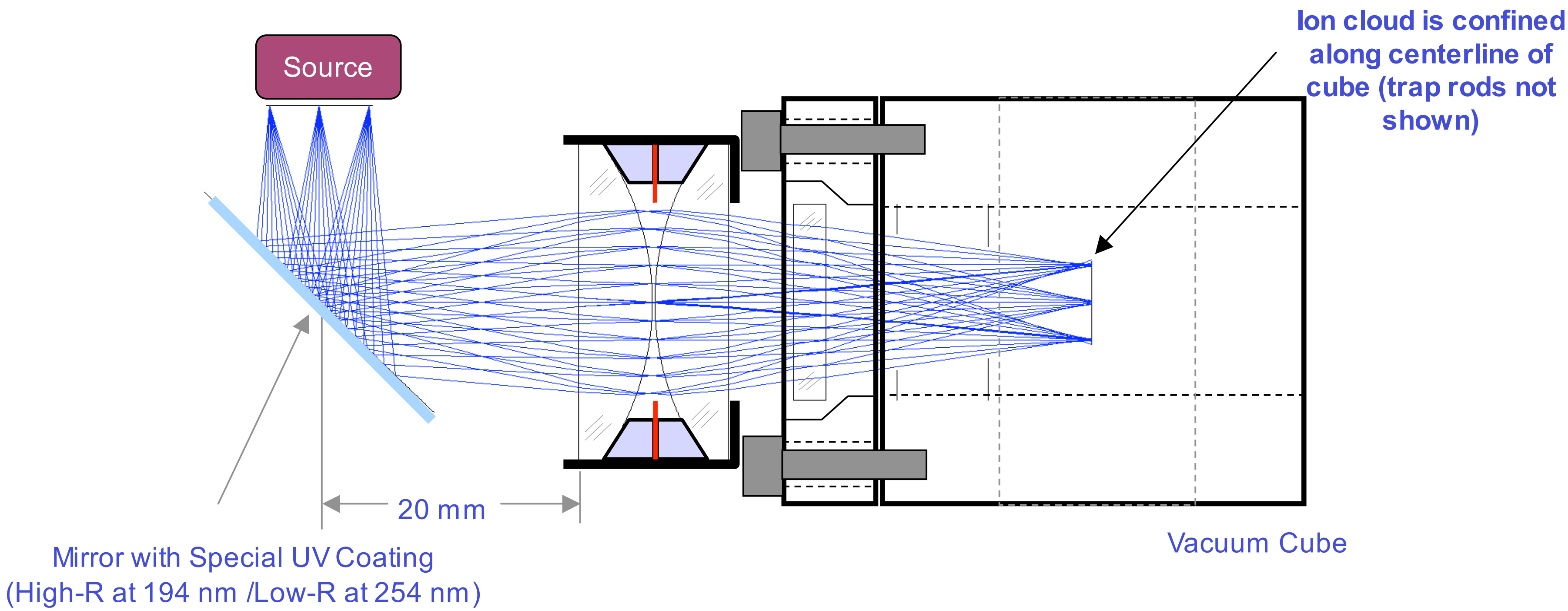


Doppler-free clock transition requires transverse k vector



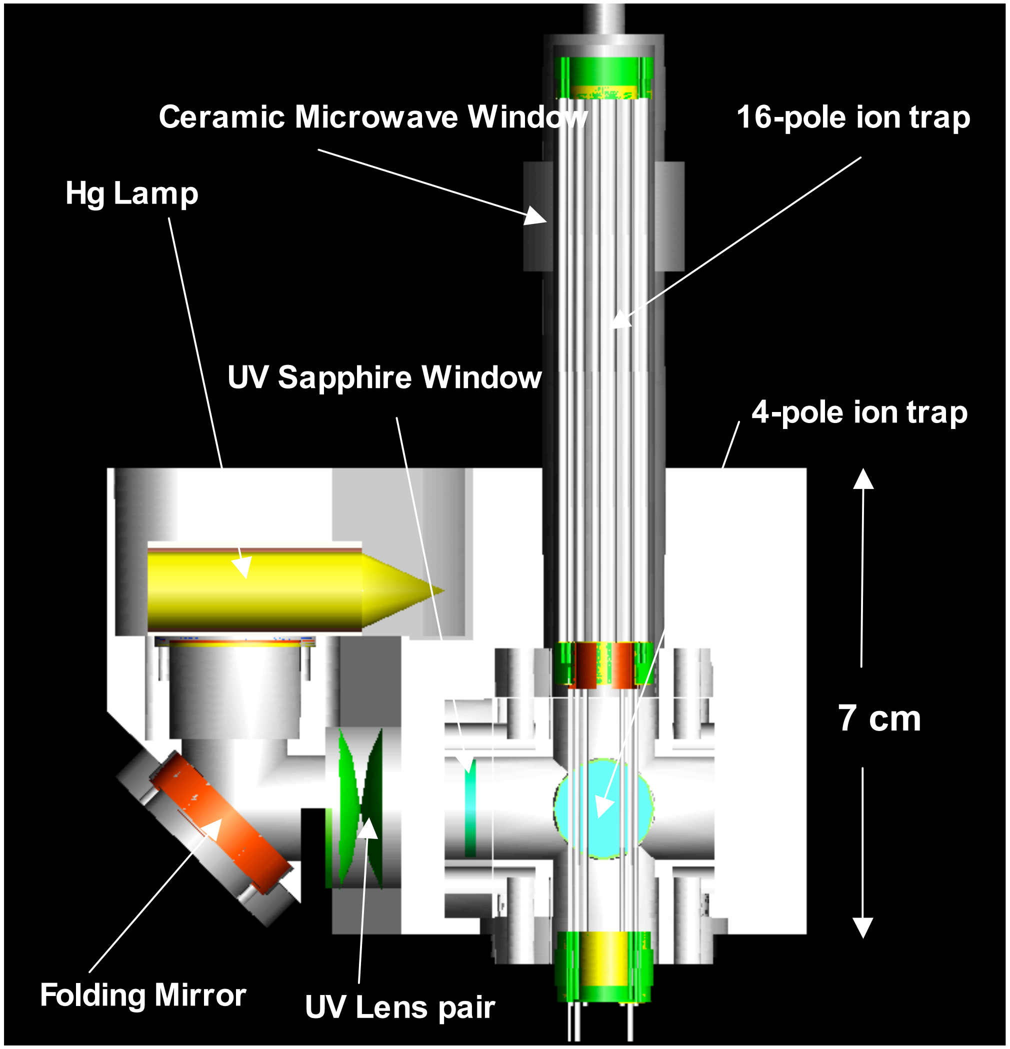
Optical System - 2 lenses and 1 mirror

- **Design Uses 3 identical optical arms, each with 2 lenses, an UV dichroic folding mirror, and a UV-grade sapphire vacuum window.**
  - **Ion fluorescence detection arms are oriented perpendicular to input light arm.**
- **Optics features:**
  - **UV-grade silica, 10-5 scratch-dig polish, antireflectance coated to <0.5% per surface.**
  - **Surface roughness is a source of stray light in the UV; laser optical polish used.**
- **Clock optical components are also used in semi-conductor photolithography (ArF 193 nm laser)**



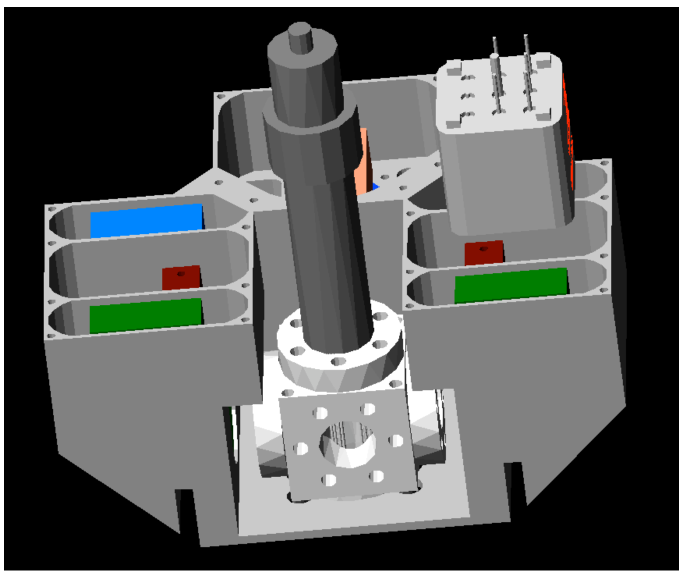
Modular Compact Optical System

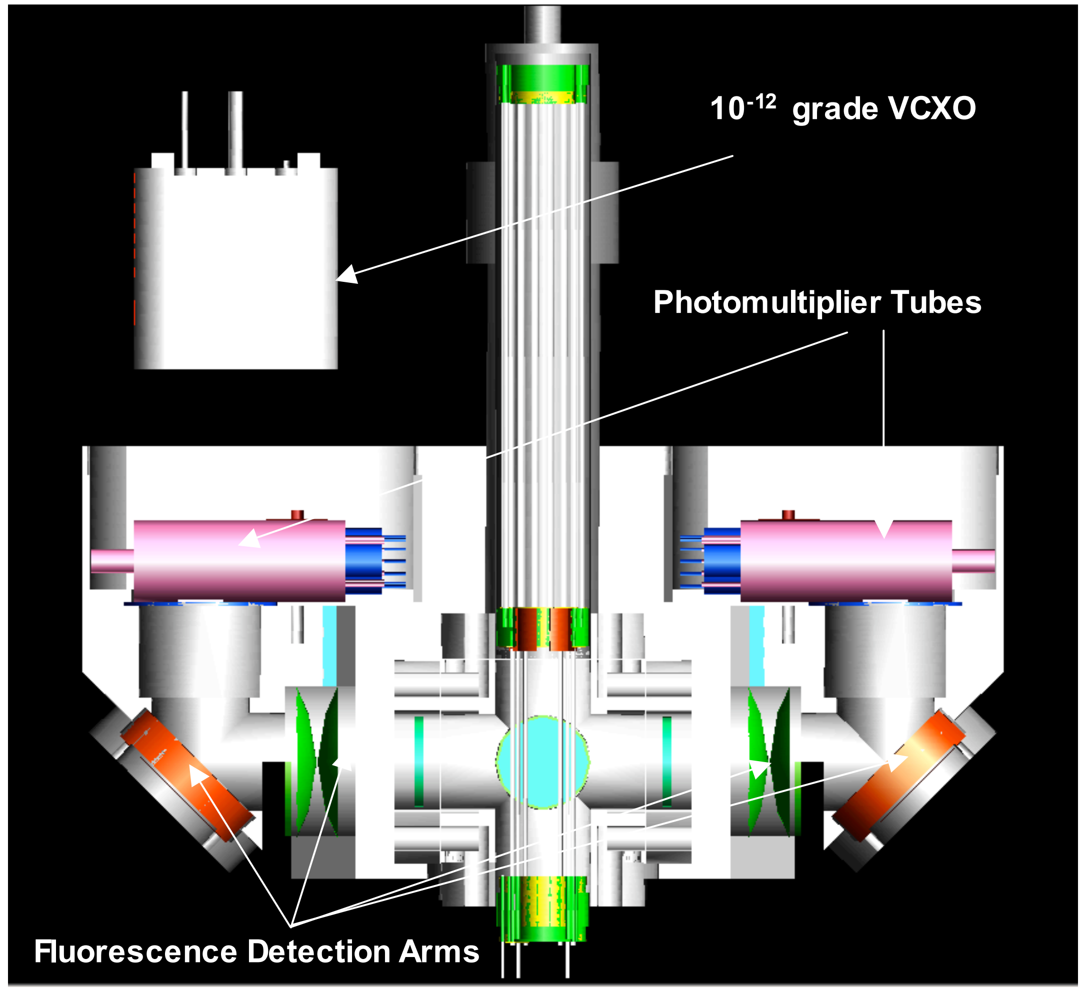
- **Optical Mount is single piece modular**
  - **can be tested for internal alignment without the ion trap**
- **Lamp resonator and exciter power electronics are integrated into module**
- **Sensitive detector electronics are isolated from lamp exciter power via RF-tight gasket compartments**



Modular Compact Optical System

- UV light detectors with power supply, amp/discriminator chip are integrated into module.
- Isolated from RF power in lamp driver module with RF-tight compartments as shown below





Compact Optical System Package

Packaged Optical Electronics - UV source and fluorescence detectors

Lamp Resonator with Hg lamp

High-Voltage supply for PMT

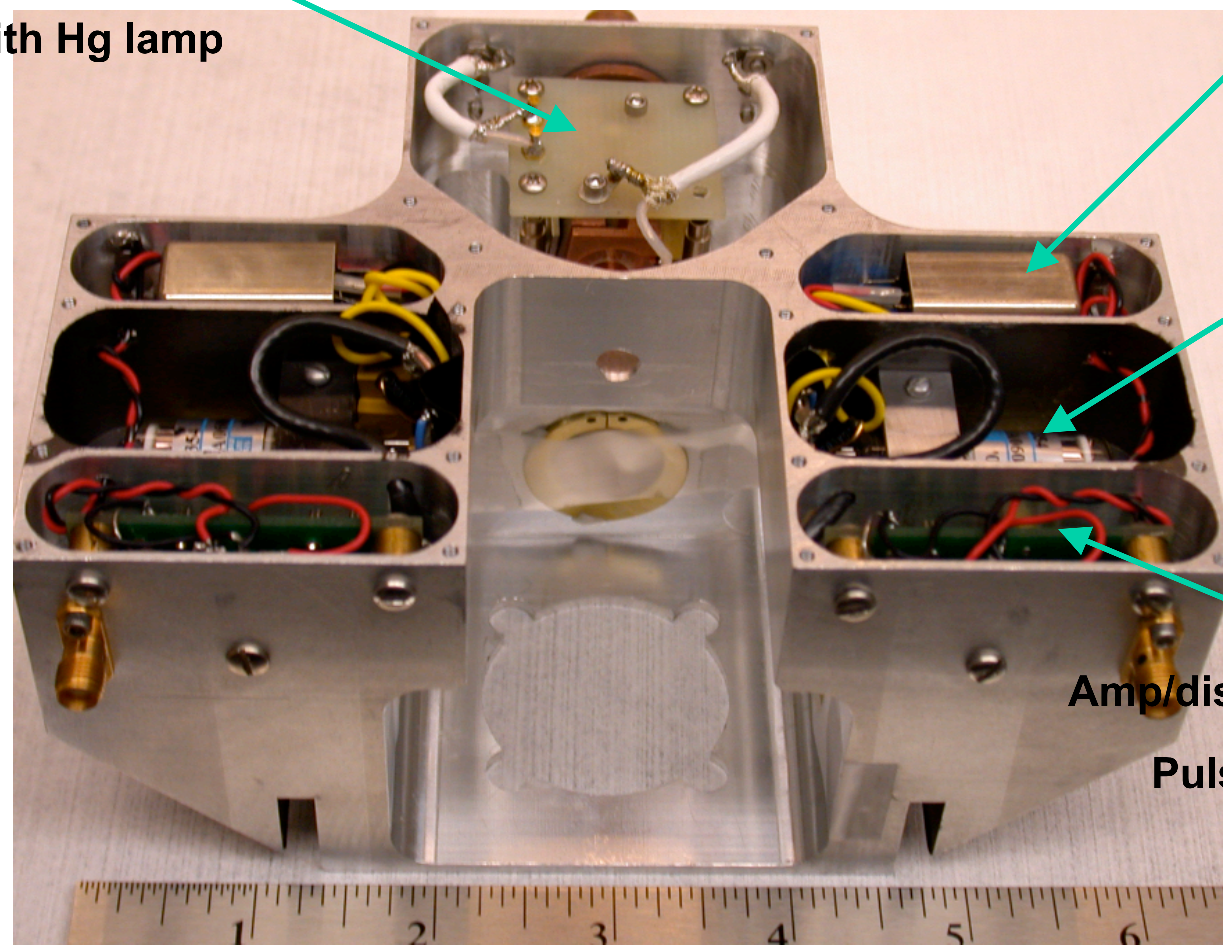


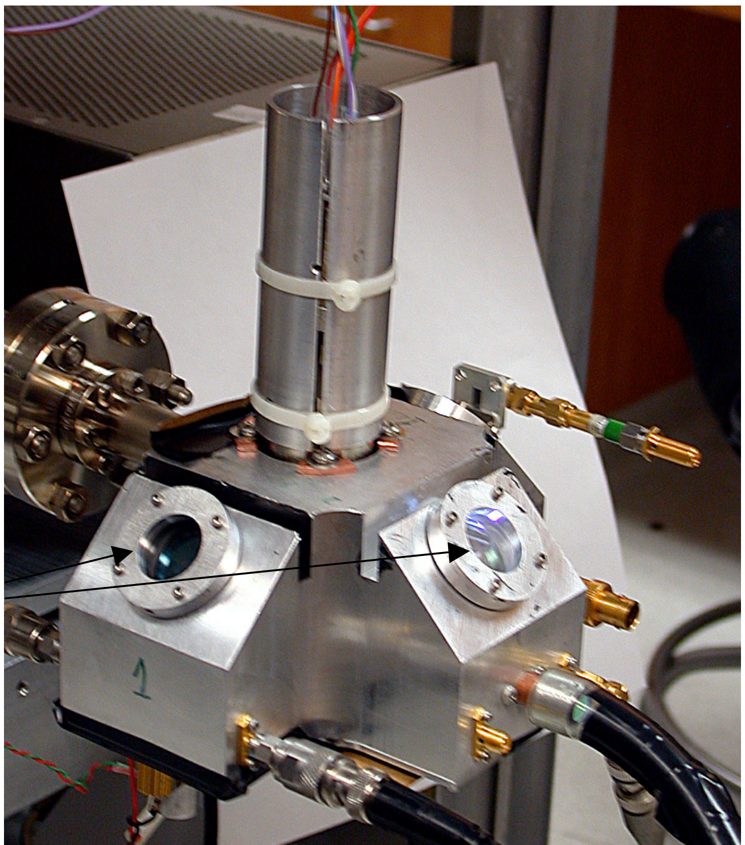
Photo-multiplier Tube (PMT) with base

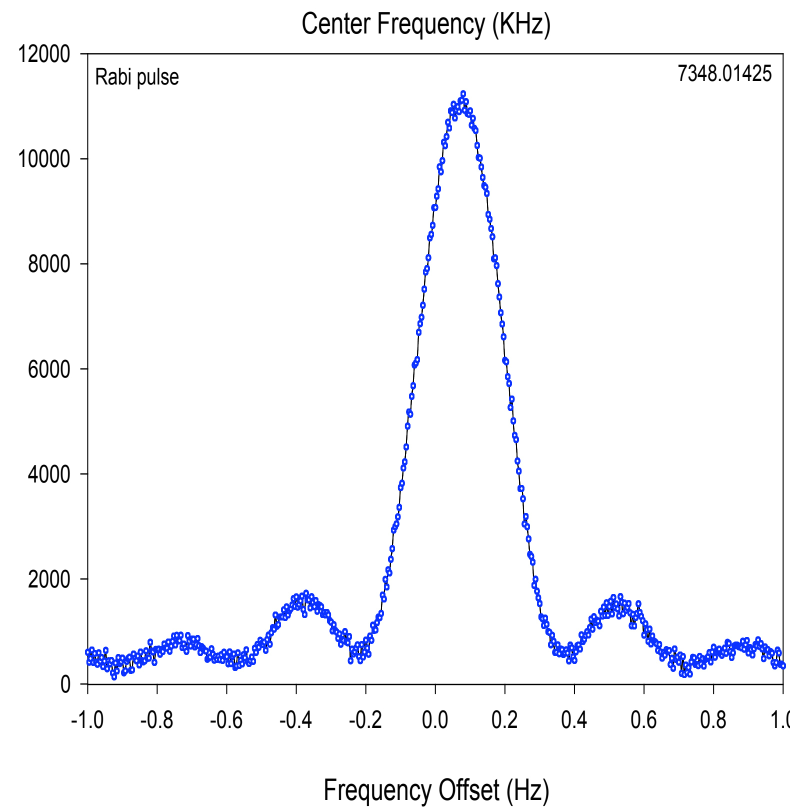
Amp/discriminator PC board Pulse out to counter

Liter Hg Ion Clock, $10^{-13}\,\tau^{-1/2}$

- Demonstrated short-term stability $10^{-13}\,\tau^{-1/2}$, as good as the 100x larger ground-based package.
- Line Q ~ 2 x 10^{11} in the first measurement (shown at right)
- No magnetic shields yet installed

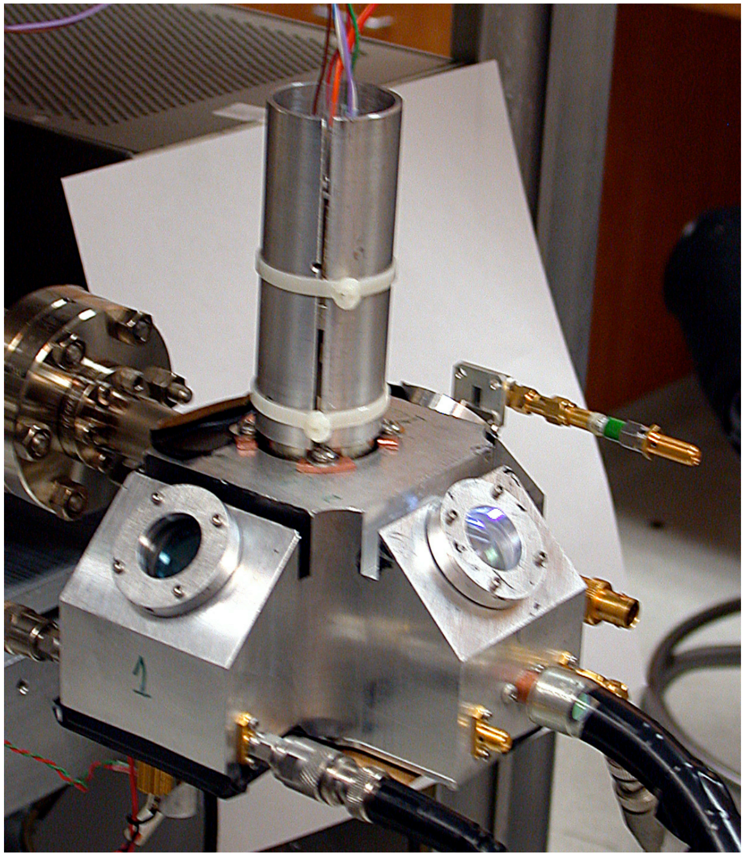
Folding Mirrors

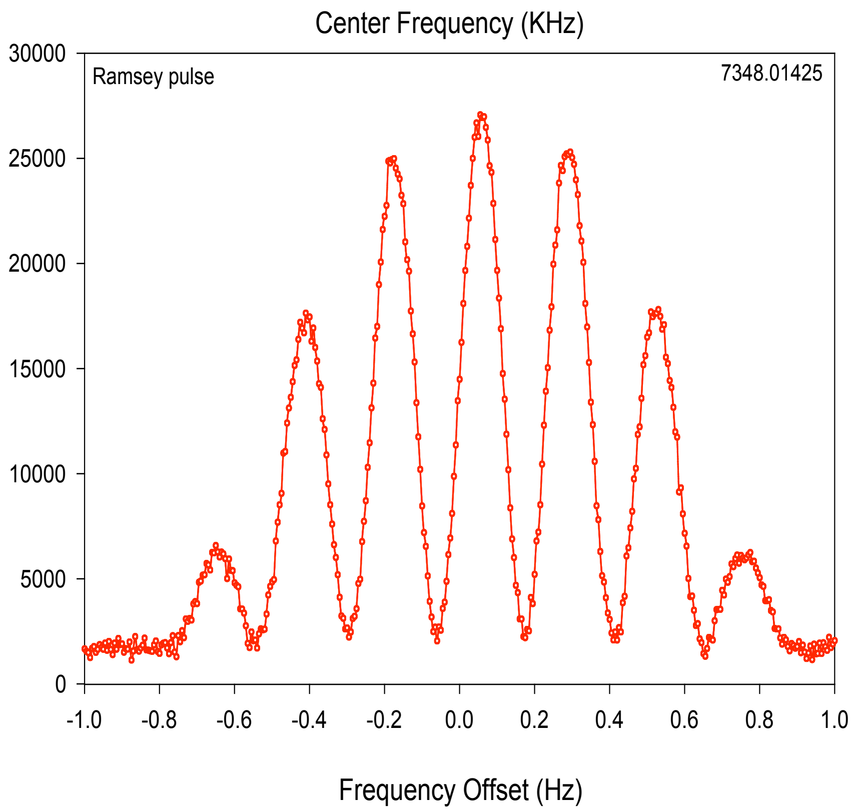




Liter Hg Ion Clock, $10^{-13}\ \tau^{-1/2}$

- $Q \sim 4 \times 10^{11}$ in measurements shown at right.
- No magnetic shields for these measurements.
- $Q \sim 10^{12}$ in later measurements.





Ion Clock Redesign - Getter Pumping

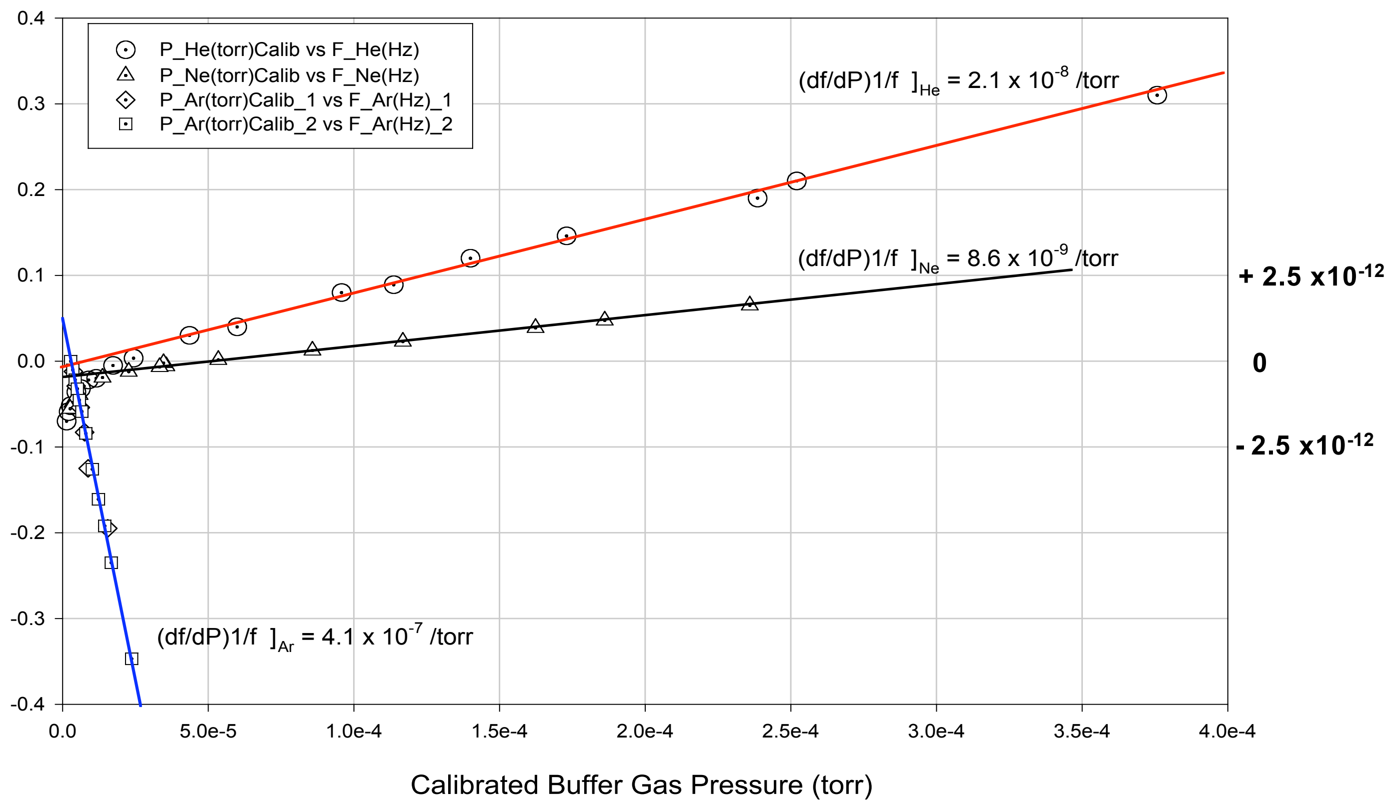
- Replace mechanical pumping and buffer-gas flow system.
  - Light, noble buffer gas required to cool ions to room temperature, increase number of captured/trapped ions.
  - UHV prepared, filled with buffer gas and getters, then sealed.

- Getter pumping, bulk and surface getters (Benvenuti, et al, 1998)
  - Consumes no mass, power, little volume.
  - Will not pump or otherwise consume buffer gas.

- Requires UHV design and fabrication.
  - 400 C Sapphire windows developed.
  - Low gas load field emitter filament employed.
  - Titanium vacuum jacket materials.
  - 400 C bake-out with sealed getters, filled to ~ 10^{-5} Torr with Ne buffer.

Ion clock uses buffer gas to “cool” ions

- Hg^{+} clock uses ~ 10^{-5} Torr “buffer” gas to cool ions to near room temperature; helium is traditionally used.
- Investigated neon and argon as substitutes; Found 3 times less clock frequency changes in neon than helium; 20x more in argon
- Additionally, neon pressure varies 5x less than helium for a 1 C temperature change
- Frequency pulling < 10^{-15} per degree C temperature change !



Summary

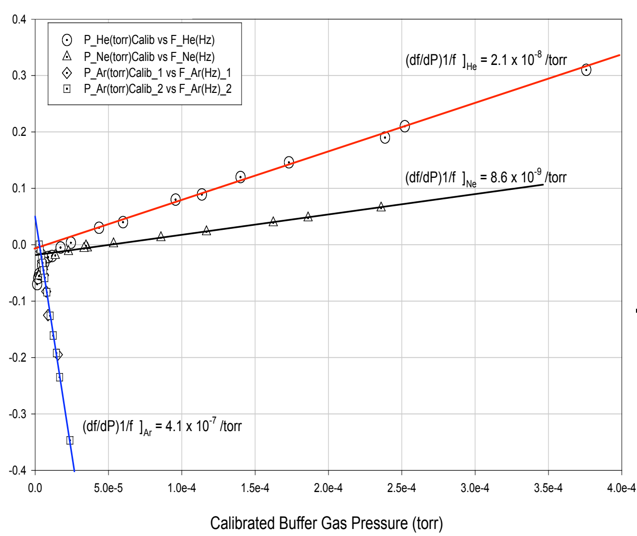
- **Microgravity friendly, 1-g gravity friendly.**

- **10^{-15} stability in a 1-2 liter package seems feasible.**

- **Demonstrated $10^{-13}\,\tau^{-1/2}$ in ~ 1-liter physics package breadboard.**

- **Demonstrated 3x reduction in buffer gas shift by neon.**

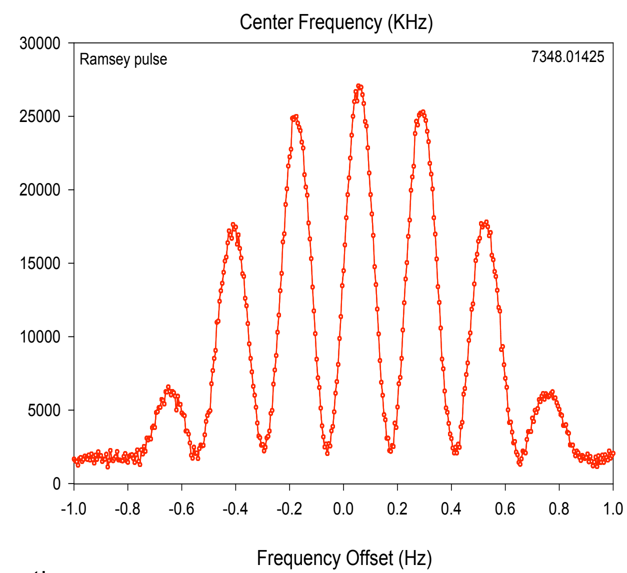
  - **Frequency pulling < 10^{-15} per degree C temperature change via buffer gas variations**



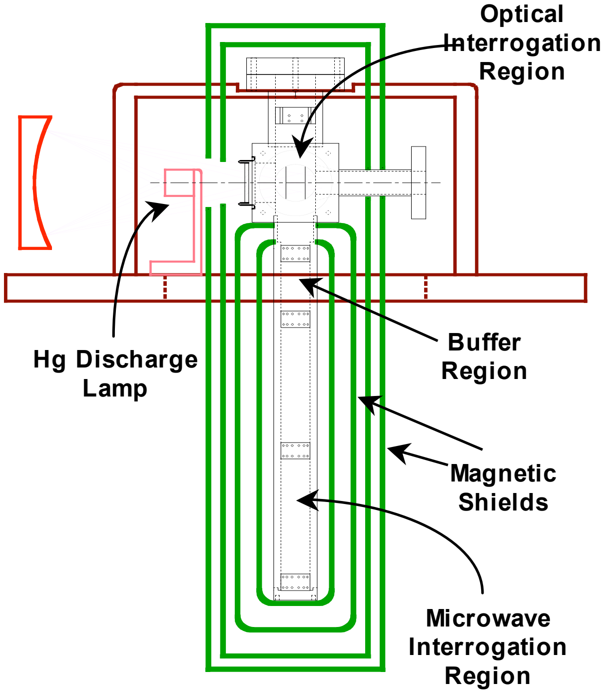
+ 2.5 x10^{-12}

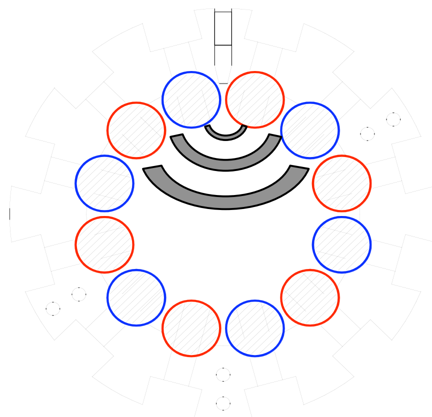
0

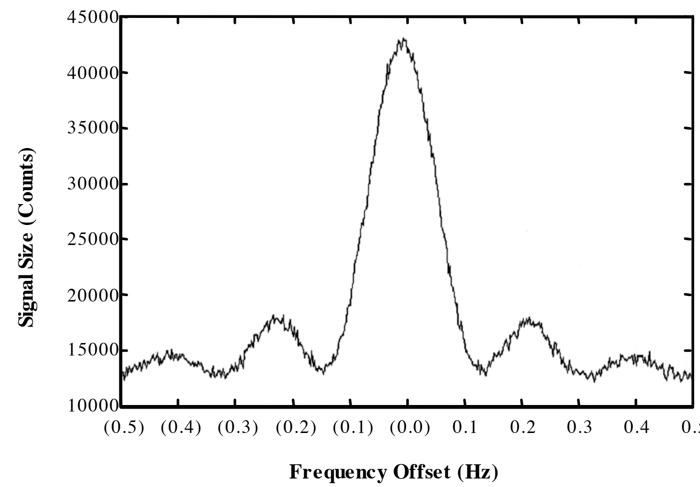
- 2.5 x10^{-12}



Doppler-free and doppler-broadened resonance in 12-pole trap





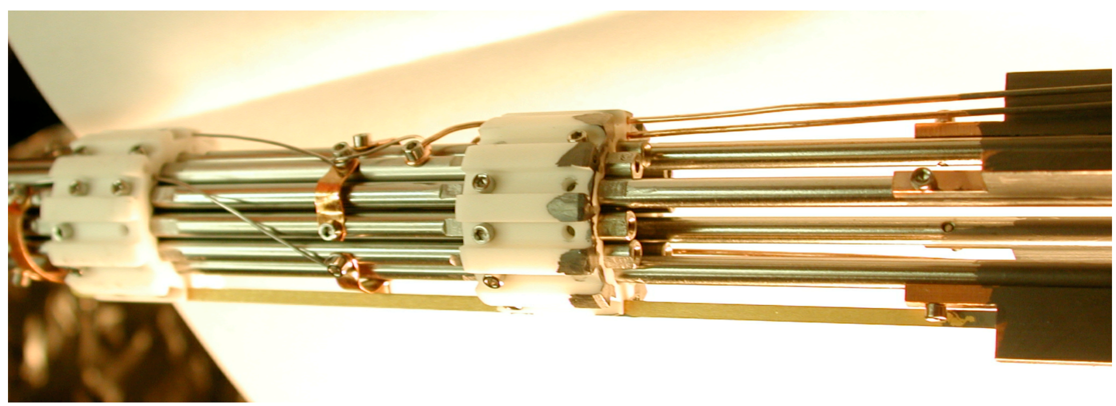


Doppler-free clock transition for transverse k vector propagation (~ 100 mHz)

Propagation along the trap axis determines Ion temperature; 1% width measure gives 2×10^{-15} 2nd Doppler determination

$$\delta\nu_{Doppler} = 2\frac{\upsilon_0}{c}\sqrt{\frac{2k_B T \ln 2}{m}}$$

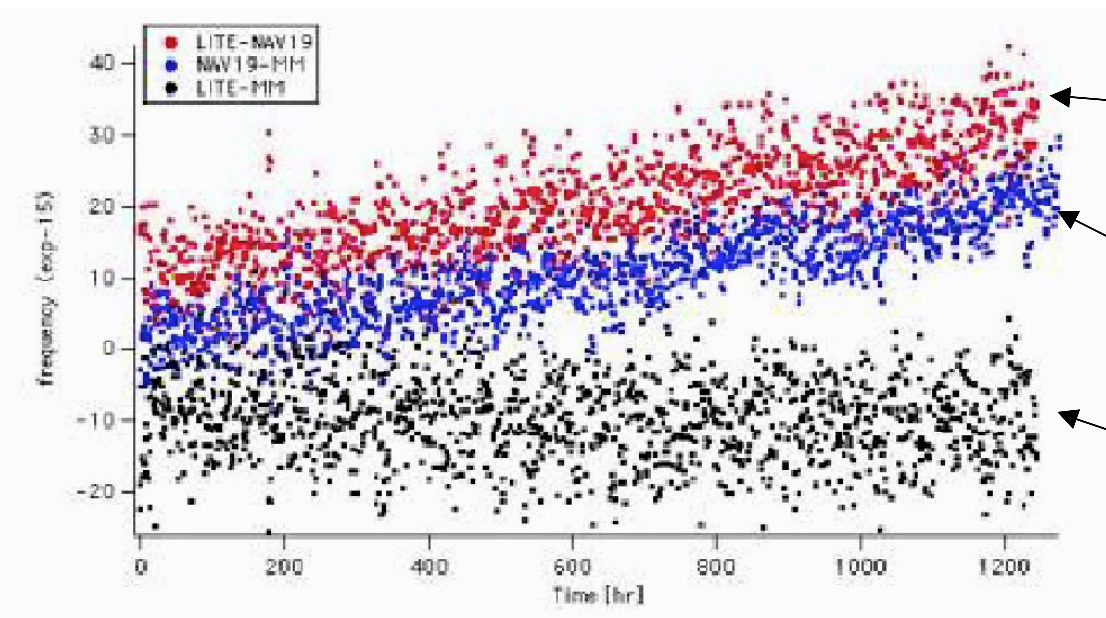
$$= 35.6\sqrt{\frac{T(K)}{300}}[kHz]$$



Ion clock redesign for space

- **Small Ion Clock Approach and Heritage**
  - **No lasers, uwave cavities, cryogenics, atomic beams, etc.**
  - **Ions are electrically shuttled between separate optical and microwave traps.**
    - **Each trap is optimized for its task: quadrupole for optical state selection; multi-pole for microwave clock.**
  - **Very good stability shown in USNO Timescale running "open loop"**

- **"Open loop" operation means no self-measurements of frequency offsets: Zeeman, ion temperature,… etc.**
  - **Fewer parts and procedures, produces stable output continuously**
- **Ion clock is not so sensitive to temperature fluctuations**
  - **Measured *unshielded* temperature coefficient of few 10^{-15} per C.**
  - **No bulky temperature isolation needed.**



Ion clock vs Nav-19 H-Maser

Nav-19 (H-Maser) vs mean of 10 H-masers

Ion clock vs mean of 10 H-Masers
Showing < 5×10^{-17} per day
Frequency drift between JPL ion clock and USNO time scale

A Superfluid Clock*

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The performance of clocks is limited by the characteristics of the underlying oscillator. Both the quality factor of the oscillator and the signal-to-noise ratio for the resonator state measurement are important. A superfluid helium Helmholtz resonator operating at ~100mK temperatures has the potential of maintaining frequency stability of $5x10^{-15}/t^{1/2}$ on the time scale of a few months. The high dynamic range of lossless SQUID position displacement measurement, and low losses associated with the superfluid flow, combined with high mechanical stability of cryogenic assemblies, contribute to the projected stability. Low overall mass of the assembly allows for multiple stages of vibration isolation.

* Work performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

Exploring the Moon and Mars Using an Orbiting Superconducting Gravity Gradiometer*

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Abstract. Gravity measurement is fundamental to understanding the interior structure, dynamics, and evolution of planets. High-resolution gravity maps will also help locating natural resources, including subsurface water, and underground cavities for astronaut habitation on the Moon and Mars. Detecting the second spatial derivative of the potential, a gravity gradiometer mission tends to give the highest spatial resolution and has the advantage of requiring only a single satellite. We discuss gravity missions to the Moon and Mars using an orbiting Superconducting Gravity Gradiometer and discuss the instrument and spacecraft control requirements.

*This research was carried out at in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

1. Introduction

Detailed knowledge of gravity is essential to understand the interior structure, dynamics, and evolution of planets. High-resolution gravity maps for the Moon and Mars will also help locating subsurface water, natural resources, and underground cavities for astronaut habitation.

Lunar Prospector provided a complete coverage of the lunar *near* side to degree and order of 75 (Konopliv *et al* 1998). SELENE, scheduled for 2005 launch, will map the entire Moon by differential VLBI radio sources and a relay satellite (Sasaki *et al* 2003). Data on the surface and subsurface structure will be obtained by terrain camera, laser altimeter, and lunar radar sounder. Mars Global Surveyor tracking data yielded a global gravity map of Mars to degree and order 80 (Smith *et al* 1999). Higher resolution will be required to locate natural resources.

There are three instrumentation options for obtaining high-resolution gravity maps: (1) a single satellite with a high-altitude relay satellite (SELENE-type), (2) satellite-to-satellite Doppler tracking (GRACE-type) (Tapley *et al* 2004), and (3) a single satellite carrying a gravity gradiometer (GOCE-type) (Rebhan *et al* 2000). By detecting the second derivatives of the potential, the gradiometer mission tends to give the highest spatial resolution. The gravity gradiometer mission also has the advantage of requiring only one satellite, minimizing the mission cost.

2. Orbit and instrument requirements

To obtain the highest gravity and spatial resolution, the altitude must be minimized. On Mars, a low-altitude gravity survey could be performed in principle by using a balloon-borne gravity gradiometer. Although the sensitivity requirement will be modest due to the low altitude, the balloon-borne survey will be an extremely slow process and will only permit very limited local surveys. A balloon experiment is not feasible on the Moon, where there is no atmosphere. Therefore, gravity survey from an orbiting spacecraft is the only means available on the Moon and a preferred means on Mars. On Mars, the satellite altitude must be kept at $h \geq 100$ km due to its atmosphere. On the other hand, a short-duration lunar gravity mission could be conducted at an altitude $h \leq 25$ km, limited only by the Moon's shape and the influence of the Earth's gravity.

Even at such a low altitude, detecting an underground cavity from the orbit is extremely challenging. For example, an underground cavity of size (50 m)^3 produces a gradient signal:

$$\Gamma = \frac{GM}{h^3} = \frac{(6.67\times10^{-11})(2.7\times10^3)(50^3)}{(2.5\times10^4)^3} = 1.4\times10^{-6}\,\mathrm{E}\,, \tag{1}$$

at $h = 25$ km, where 1 E ≡ 10^{-9} s^{-2}. It may be possible to reduce h to 10 km over a limited area by using a slightly elliptical orbit. The signal then increases to Γ ≈ 1.8 x 10^-4 E. With the orbital speed of 1.6 km/s, it takes $t \approx 6$ s to traverse 10 km. The required measurement bandwidth, $\Delta f \approx 1/t \approx 0.16$ s, then leads to a gradiometer sensitivity requirement:

$$S_\Gamma^{1/2}(f) \leq \frac{\Gamma}{\sqrt{\Delta f}} = \frac{1.8\times10^{-4}}{\sqrt{0.16}} = 4.5\times10^{-4}\,\mathrm{E\,Hz^{-1/2}}\,,\ 0.1\,\mathrm{Hz} \leq f \leq 0.2\,\mathrm{Hz}. \tag{2}$$

To be able to identify the signal, the background gravity feature must also be known to this level.

3. Superconducting Gravity Gradiometer

To meet the demanding sensitivity requirement of 10^{-4} E Hz$^{-1/2}$, a superconducting gravity gradiometer (SGG) operating at $T \leq 4$ K is required. A three-axis SGG has been developed at the University of Maryland with Code-Y support for Earth orbit application (see Figure 1). The intrinsic noise of this instrument was 4 × 10^{-3} E Hz$^{-1/2}$, limited by the relatively stiff mechanical suspension used (Moody and Paik 2002). One could vastly improve the sensitivity of the SGG by employing magnetically levitated test masses.

Figure 2 is a schematic of the SGG with magnetically levitated test masses. The upper figure shows two levitated test masses along with levitation and sensing coils. The lower figure shows the superconducting differential circuit. Persistent currents I_1 and I_2 stored in the two sensing

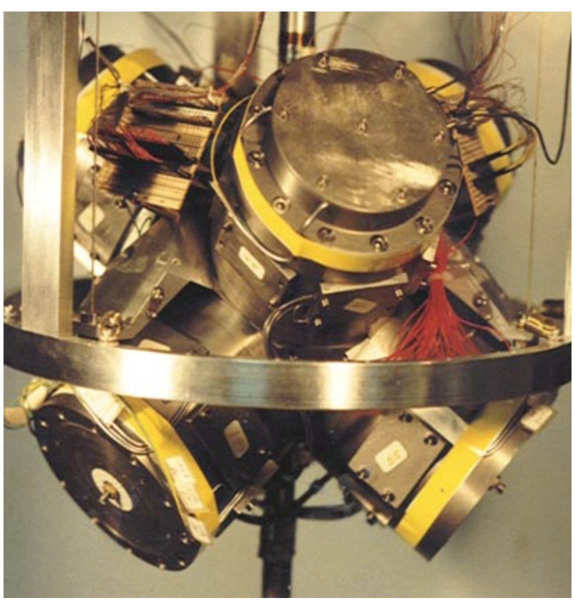

Figure 1. SGG developed for space application.

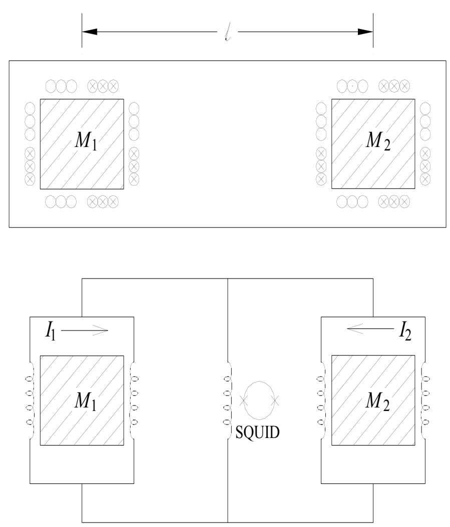

Figure 2. Schematic of SGG with magnetically levitated test masses.

loops provide coupling between the displacement of the test masses and the SQUID. The ratio I_1/I_2 is adjusted to precisely balance out common-mode acceleration at the SQUID output.

The intrinsic gradient noise of an SGG can be shown to be (Chan and Paik, 1987)

$$S_\Gamma(f) = \frac{8}{m\ell^2}\left[k_B T\frac{\omega_0}{Q} + \frac{\omega_0^2}{2\beta\eta}E_A(f)\right], \tag{3}$$

where m, $f_0 = \omega_0/2\pi$, and Q are the mass, resonance frequency, and quality factor of the test mass; ℓ is the gradiometer baseline; β, η, and $E_A(f)$ are the transducer energy coupling constant, amplifier coupling efficiency, and SQUID energy resolution; and $f = \omega/2\pi$ is the signal frequency, respectively. With the same parameter values as the mechanically suspended SGG except for f_0: $m = 1.0$ kg, $\ell = 0.2$ m, $f_0 = 0.2$ Hz, $T = 2$ K, $Q_0 = 10^6$, $2\beta\eta = 0.5$, $E_A(f) = 5 \times 10^{-31}$ J Hz^{-1} $(1 + 0.1$ Hz$/f)$, one finds $S_\Gamma^{1/2}(f) = 8 \times 10^{-5}$ E Hz$^{-1/2}$ at $0.01 \text{ Hz} \leq f < 0.2$ Hz.

4. Spacecraft control requirements

For cooling the SGG, a liquid helium cryostat will be the simplest option for a lunar gravity mission since it requires a lifetime of only three to six months. For a Mars gravity mission, a liquid helium cryostat, supported by even a noisy cryocooler, will work. En route to Mars, the cryocooler can be used to conserve liquid helium. During the orbital operation, the cryocooler can be turned off so the instrument can be cooled by the quiet liquid helium cryostat.

To minimize the centrifugal acceleration error, the gradiometer must be in an inertial orientation. On the other hand, to minimize the attitude control and dynamic range requirement, the gradiometer must be in a planet-fixed orientation. Only one axis, the orbit normal, satisfies both of these requirements. Therefore, to obtain the best sensitivity, a single-axis SGG could be carried by a spacecraft in an inertial orientation, with its sensitive axis normal to the orbit plane.

With the SGG's common-mode rejection ratio of 10^7, the spacecraft linear acceleration must be controlled to 10^{-7} m s^{-2} Hz$^{-1/2}$. The attitude, attitude rate, and attitude acceleration control requirements are 10^{-4} rad, 10^{-7} rad s^{-1} Hz$^{-1/2}$, and 10^{-6} rad s^{-2} Hz$^{-1/2}$, respectively. The linear acceleration control requirement could be met without a drag-compensation system. The attitude control requirement, although demanding, could be met by combining star trackers with gyros.

Acknowledgment
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Applied Superconductivity and Superfluidity for Exploration of the Moon and Mars*

Talso Chui
Jet Propulsion Laboratory, California Institute of Technology

The initiative for human exploration of the Moon and Mars presents great technical challenges as well as new opportunities for scientific investigations. I will discuss recent developments in superconductivity and superfluidity that can be applied to solve some of these technical challenges. This includes biomedical imaging of astronauts using an array of SQUID magnetometers; resource exploration using SQUID as well as a SQUID-based gravitational gradiometer; measurement of rotational jitter of the Moon and of Mars, for improvement in GPS using a superfluid gyroscope; and the concept of a high precision superfluid clock recently proposed for navigation at JPL. Physicists can also participate as explorers in the Moon/Mars initiative. I will discuss a proposed experiment to search for the postulated strangelet particle (a dark matter candidate) by using the Moon or Mars as a giant detector. As suggest by Nobel Laureate Sheldon Glashow, a massive (~ 1 ton) strangelet can generate a trail of seismic waves, as it traverses a celestial body. The pristine environments of the Moon and Mars, with their very low seismic backgrounds, are ideal for such an experiment. Very sensitive SQUID-based seismometers can be deployed to increase the sensitivity of strangelet detection.

*This work performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Development of Superfluid Interference Gyroscopes

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University of California, Berkeley

This talk will describe our progress in developing a superfluid analog of the dc SQUID. Such a device can measure small rotation changes, with sufficient sensitivity to complement conventional seismology and possibly geodesy. We will discuss our proof of principle experiment using ^3He, our plans to make an enhanced sensitivity device, and the exciting possibility of using even ^4He at 2000 times higher temperature.